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BUILDING THERMAL ENERGY STORAGE

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BUILDING THERMAL ENERGY STORAGE

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Preface

The work for the present PhD thesis was carried out at the International Centre for Indoor Environment and Energy (ICIEE), Department of Civil Engineering at the Technical University of Denmark (DTU) in the period between June 2010 and March 2014 under the supervision of Professor Ph.D. Bjarne W. Olesen. The thesis was done as part of “Work Package 3: New Intelligent Building Technologies” of the Strategic Research Centre for Zero Energy Buildings at Aalborg University.

First of all, I would like to express my sincere gratitude to my supervisor Professor Bjarne W. Olesen for his valuable advice, guidance and discussions, and encouragement throughout my Ph.D. study.

My sincere thanks to all co-authors of my papers: Bjarne W. Olesen, Ongun Berk Kazanci, Martynas Skrupskelis, and Pavel Sevela. I am grateful for their help and co-operation, and valuable feedback on my research work.

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Also I would like to thank the always helpful and co-operative technical staff at the ICIEE Laboratory, Peter Slotved Simonsen and Nico Henrik Ziersen, for the extraordinary efforts and support in building up and testing the experimental set-up, and running the experimental case studies.

Warm thanks to my colleagues at the International Centre for Indoor Environment and Energy for all the inspiration and good time spend together. I really enjoyed working among you.

Special thanks to my parents and my sister, for their never ending support.

And last but not least, thanks to my beloved wife Angela for the support and encouragement, and for withstanding my absence in the finishing stages of the Ph.D. work.

Kongens Lyngby, April 2014

Georgi Krasimirov Pavlov

Abstract

The main objectives of this thesis have been to investigate and provide the basis for the development of new intelligent thermal energy storage possibilities for space heating and space cooling applications.

The selection of a thermal energy storage system mainly depends on the storage period required, economic viability and operating conditions. Well designed TES systems can reduce initial and maintenance costs and can significantly reduce energy use and demand. Increased flexibility of operation, improved indoor environmental quality, conservation of fossil fuels and reduced pollutant emissions are other benefits. A coordinated set of actions for improved TES designs are needed if the potential benefits are to be fully realized.

In the present work different thermal energy storage systems have been investigated, including seasonal storage in the ground, building thermal mass utilization, and phase change materials for building's thermal mass enhancement. The thesis comprises of a review of existing literature in the field of thermal energy storage for heating and cooling applications in buildings; a parametric study, employing an advanced simulation model in TRNSYS 17, evaluating the efficiency and potential benefits of the use of PCM-gypsum ceiling panels to enhance the thermal mass and to improve the cooling load management of lightweight office buildings; and an experimental study in a climate chamber in which the performance of ceiling panels with PCM is evaluated for a typical office environment, in terms of temperature control and cooling load management, through a series of experimental case studies.

Within the limitations of this thesis and based on the findings from all parts and papers it comprises some important outcomes were presented. Seasonal ground thermal energy storage of solar heat is technically feasible concept and work well as part of central solar heating plants with seasonal storage. Solar fractions of up to 57% of total delivered heat have been achieved. However, construction costs of and thermal losses from the seasonal storages are still too high. Additional drawback is the high level of system complexity which may alter significantly the efficiency and potential benefits.

Underground thermal energy storage with ground- source heat pumps for heating and cooling applications in buildings offers economic as well as environmental advantages in terms of energy savings and greenhouse gas emissions. Since the ground-coupled system functions both as a heat source and a heat sink, these double-effect storage projects may provide high energy savings (up to 77% in different projects).

Utilization of buildings thermal mass in office buildings reduces the diurnal temperature swings and the daytime peak temperatures. High thermal mass contributes significantly in the net cooling demand reduction of the building through daytime cooling load reduction and shifting of the cooling demand to night-time hours, which was valid for both passive and active thermal mass utilization concepts. The quantity of the achievements is dependent on the amount of exposed thermal mass, night ventilation or night-time embedded pipes cooling strategy, set-point temperatures, occupancy patterns, and daytime ventilation airflow rates.

PCM-plasterboard and PCM-clayboard ceiling panels offer significant benefits for thermal mass enhancement in lightweight buildings and retrofitting. Reduced diurnal temperature swings and daytime peak temperatures are among the benefits. Additionally, significant energy savings, peak cooling load reduction and cooling demand shifted from peak to off peak hours were achieved. The obtained benefits are dependent on the PCM melting temperature and the PCM-building material composite thermal conductivity. PCMs with melting temperature range towards the lower boundary of the desired indoor temperature variation range were shown to be more beneficial in terms of room temperature control, while increase of the thermal conductivity resulted in increased thermal performance of the ceiling panels. Limitations of the concept have been identified I terms of slow heat absorption rate of the ceiling panels, and high cost of the used in them microencapsulated PCM.

Resumé

Hovedformålet med projektet har været at undersøge og kortlægge mulighederne for udvikling af nye intelligente metoder for termisk lagring I forbindelse med opvarmning og køling af bygninger.

Hvilken form for termisk lagring (TES) der skal vælges afhænger af den ønskede lagringstid, økonomi og drift betingelser. Et godt planlagt TES system kan reducere installation og vedligeholdelses udgifter og kan signifikant reducere energi forbrug og behov. Andre fordele er en fleksibel drift, forbedret indeklima, reduceret brug af fossile energikilder og emission til omgivelserne. For fuldt at udnytte fordelene ved TES er det nødvendigt at forbedre design og dimensionering.

I nærværende projekt er forskellige typer af termiske energilagre (TES), som lagring i jorden, udnyttelse af bygningens termiske masse og fase skiftende materialer (PCM), blevet undersøgt. Rapporten omhandler:

Et litteraturstudie af mulige former for termisk lagring til køling og opvarmning af bygninger;

Et parameter studie, hvor en avanceret simulations model i TRNSYS17 anvendes til at undersøge hvorledes gips plader med PCM kan forbedre effektiviteten af køling i lette kontorbygninger;

Et laboratorium eksperiment hvor effekten af loftpaneler med PCM på regulering af rumtemperature og optimering af køleeffekten er blevet undersøgt.

Inden for begrænsningerne af dette projekt og baseret på resultaterne fra alle undersøgelser og publikationer er der fundet ny viden. Sæson lagring i jorden af solenergi er en mulighed og virker fint som en del af et centralt solvarmesystem. Ved termisk lagring der kan opnås op til 57 % af den totale leverede energi. Konstruktions omkostninger og transmissions tabene for sådanne lagre er dog stadig for høje. Andre ulemper er kompleksiteten af systemerne

Lagring eller udveksling af termisk energi I jorden med en jordvarmepumpe til opvarmning og køling er derimod en økonomisk såvel som en miljørigtig løsning med hensyn til energiforbrug og emission til omgivelserne. En jordvarme-veksler fungerer således både som en varmekilde (vinter) og en varmesænke (sommer). Denne dobbelteffekt kan medføre energibesparelser helt op til 77 %.

Brug at den termiske masse i en kontorbygning kan reducere dagsvingninger og spidsbelastninger om dagen af rum temperaturen. En højere termisk masse medfører en signifikant reducering af kølebehovet i en bygning ved at reducere kølebelastningen om dagen og udskyde en del af kølingen til nattetimerne. Dette gælder både for en passiv udnyttelse som en aktiv udnyttelse af den termiske masse. Hvor meget der kan opnås afhænger af hvor meget termiskmasse der er eksponeret, nat ventilation eller integrerede rør til køling, sætpunkttemperature, brugsmønster og hvor meget der ventileres i løbet af dagen.

Loftpaneler med integreret fase skiftende materiale (PCM) er en god mulighed til at forøge den termiske masse i en letvægts ny- bygning eller ved renovering. Reducering af dagsvingninger og maksimal rumtemperatur om dagen er nogle af fordelene. Desuden kan der opnås betydelige energibesparelser, reducering af spidsbelastninger og forskydning af kølebehov til natten. De opnåede fordele er afhængige af PCM smeltetemperatur og PCM panelets sammensætning (varmeledningsevne). PCM materialer med et smeltepunkt i den nedre del af komfortintervallet og en højere varmeledningsevne er bedre med hensyn til at kontrollere rumtemperaturen. Begrænsningerne er ofte en for langsom varmeovergang mellem panelerne og rummet og høje priser for PCM materialer.

Contents

Part I: Introduction, Objectives and Thesis Outlines

The first part of the thesis gives a brief introduction to thermal energy storage in buildings, including potential benefits, general criteria for design and evaluation, and types of thermal energy storage systems for heating and cooling applications. The general objectives of the thesis are defined and the part concludes with an overview of the following parts of the thesis.

1. Introduction

1.1 Background

The buildings' sector accounts for about 40% of the total energy use in the European Union (EU) countries (International Energy Agency, IEA 2009). However, at the same time the buildings' sector has a documented cost-effective savings potential of up to 80%, which can be effected over the next 40 years. In order to ensure these considerable energy conservations and at the same time to apply renewable energy in an optimal way, the development of integrated, intelligent technologies for buildings is needed.

Energy demand in commercial, industrial and residential sectors vary on a daily, weekly and seasonal basis. This demand can be matched with the help of thermal energy storage (TES) systems that operate synergistically and are carefully matched to each specific application. Thermal energy storage is the temporary storage of high- or low-temperature energy for later use. Examples of TES are the storage of solar energy for overnight heating, of summer heat for winter use, of winter ice for space cooling in summer, and of the heat or cold generated electrically during off-peak hours for use during subsequent peak demand hours.

The use of TES for applications as space heating and cooling has recently received much attention (Dincer & Rosen 2011, Dincer 2002). A variety of new TES techniques have been developed over the past four decades. The selection of a TES system mainly depends on the storage period required (e.g., diurnal or seasonal), economic viability, and operating conditions. These systems have the potential of making the use of thermal equipment more effective and for facilitating large-scale substitutions of energy resources economically. TES systems can be an important means of offsetting the mismatch between thermal energy availability and demand. Well designed systems can reduce initial and maintenance costs and energy use and demand (Dincer & Rosen 2011, Dincer 2002, Dincer & Dost 1996, Dincer et al. 1997). In general, a coordinated set of actions is needed in several sectors of the energy system for realization of the maximum potential benefits of TES.

Many research and development activities on energy have concentrated on efficient energy use and energy conservation, and TES is one of the more attractive thermal technologies that have been developed. Efficient TES systems minimize thermal energy losses and attain high energy recovery during the extraction of the stored thermal energy with little degradation in temperature. Many researchers have cited Exergy as the most appropriate tool for analyzing TES efficiency and performance (Dincer 2002, Dincer & Dost 1996, Dincer et al. 1997, Bjurstrom & Carlsson 1985, Rosen 1992, Gunnewiek et al. 1993, Dincer & Rosen 2001).

Increasing energy demands, shortages of fossil fuels and environmental concerns are increasing the interest in the development of renewable energy sources. Such sources, as solar energy, have intermittent nature and their effective utilization is dependent on the availability of efficient and effective thermal energy storage systems. Different examples about the efficient utilisation of natural and renewable energy sources, cost savings and increased efficiency achievable through the use of TES could be considered (Dincer & Rosen 2011).

In continental climates, it is necessary to provide heating in winter and cooling in summer. Typically, these services are provided by using energy to drive heaters and air-conditioners. With TES it is possible to store heat from the warm summer months for use in winter, while the cold ambient temperatures of winter can charge a cool store to provide cooling in summer. This example of seasonal storage can help to meet the energy needs cause by seasonal fluctuations in temperature. Such a scheme requires a great storage capacity because of the large storage timescales. The same principle can be applied on a small scale to smooth out daily temperature variations. For example, solar energy can be stored during the day and used for night heating.

Another example is the use of thermal energy storage to take advantage of off-peak electricity tariffs. Chiller units can be used to cool a thermal storage at night, when the cost of electricity is relatively low. The storage then provides cooling for air conditioning throughout the day. In that way electricity cost are reduced, the efficiency of the chiller is increased because of the lower night-time ambient temperatures and the peak electricity demand for electrical supply utilities is reduced.

1.2 Benefits of Thermal Energy Storage for Heating and Cooling Applications in Buildings

TES is a mature technology that has been applied successfully in commercial and institutional building applications. In Dincer & Rosen (2011) is pointed out that the advantages of TES exceed the disadvantages. The benefits of utilising TES systems can be divided in three main groups – benefits for the building owner/tenant, benefits for the environment and society, and benefits for the energy provider. Some of them are summarized here:

Benefits for the building owner/tenant

- Reduced heating and cooling costs by shifting a building’s energy demand from on-peak to off-peak periods.
- With a TES system, reduced system component’s size can be achieved. Using smaller chillers, air handling units, fans, ducts, and pumps can reduce system initial costs.
- Using TES in heating and cooling applications can increase the building’s load factor for electricity so less expensive electricity rates can be obtained from the energy providers.

Energy Storage benefits for the environment and society

- TES storage helps make renewable energy resources more viable.
- Distributes the energy to the buildings at night when line losses are low and generation efficiencies are high.
- Increases the load factor of generation.
- Eliminates the need for additional power plants to be used during peak demand periods.
- Thermal energy storage reduces source-energy consumption, which means that energy providers will generate fewer polluting emissions.

Energy Storage benefits for the energy provider

- TES systems reduce peak electrical demand, allowing energy providers to produce more electricity at increased efficiencies and avoid costly expansion.
- Electricity is produced and delivered much more efficiently during off-peak hours than during on-peak periods. For every kilowatt-hour of energy that is shifted from on-peak usage to off-peak, there is a reduction in the source fuel needed to generate it. The reduction in source fuel normally results in a reduction of greenhouse-gas emissions produced by the power plant.
- Use of thermal energy storage increases a utility's load factor.

1.3 Criteria for Design and Evaluation of Building Thermal Energy Storage systems

The different thermal energy storage concepts have very different characteristics, possible applications, strength and weaknesses. There are numerous criteria to evaluate TES systems and applications such as technical, environmental, economic, energetic, sizing, feasibility, integration, and storage duration (Dincer & Rosen 2011). Each of these criteria should be considered carefully to ensure successful TES implementation. Some important technical and economic aspects are briefly considered here.

The first step of a TES project is to determine the energy load profile of the building (or a complex of buildings). Commercial, institutional and residential buildings all have different energy load profiles. The demand and load profile for heating and cooling is not only building type specific, but also varies for buildings of the same type. Important parameters influencing the load profile of the building are use of the building, internal loads, and the climatic conditions.

The following steps are to determine the types of storage appropriate for the particular application, the amount of storage required, the effect of storage on system performance, reliability and costs, and the storage systems or designs available.

In practice it is useful to characterize the different type of TES depending on the storage duration: short-, medium-, or long-term. Short-term or diurnal storage is used to address peak power loads lasting from few hours to a day in order to reduce the sizing of the HVAC system and take advantage of energy-tariff daily structures. Medium- or long-term storage, also referred to as annual or seasonal storage, is recommended when waste heat or seasonal energy loads can be transferred with a delay of a few weeks to several months.

The primary characteristic of a seasonal storage system is the very large capacity that is required (in the order of a hundred times the capacity of a daily storage). Thermal losses become very important for such long-term storage. While diurnal systems can generally be installed within a building, seasonal storage requires frequent additional locations.

Related to the amount of storage required, a need exists for improved TES-sizing techniques, to avoid both under-sizing and oversizing of the storage. Under-sizing can result in poor levels of indoor comfort, while oversizing results in higher initial costs and waste of electricity or other primary energy if more energy is stored than is required. Proper installation and control is a requirement for successful TES-sizing. Depending on if the system includes full, partial, or demand-side storage, proper operation and control strategies should be developed.

The effect of TES on the overall energy system performance should be evaluated in details. Inherent benefits from the use of TES like increased generation capacity and system efficiency should be evaluated. The potential for more effective use of thermal energy equipment and the storage integration with the building energy supply system has to be investigated in detail. The related advantages in reduced electricity and other primary energy are of high importance.

Financial analysis for TES-based projects can be complex. The economic justification for storage systems normally requires that the annualized capital and operating costs for TES be less than those required for primary generating equipment supplying the same service loads and periods. TES systems accrue fuel cost savings relative to conventional primary generating equipment, but often at the expense of higher initial capital cost. Economic evaluation and comparison parameters often determined include the simple payback period. Payback periods of more than ten years and higher initial costs are often obstacles for the broad acceptance of TES systems by engineers, building owners and investors.

1.4 *Thermal Energy Storage Systems for Heating and Cooling Applications in Buildings*

Depending on the thermodynamics of the storage process, the TES systems that receive consideration in building applications are classified as sensible thermal energy storage systems and latent thermal energy storage systems. In sensible TES, energy is stored by changing the temperature of a storage medium. Sensible storage systems commonly use bricks, concrete, rocks, ground, or water as a storage medium. Latent TES systems store energy in phase change materials (PCMs), with the thermal energy stored when the material changes phase (the transition solid ↔ liquid with no change in temperature).

In practice, it is more favorable to characterize the different types of TES depending on the storage duration: short-term (diurnal) storage; or long-term (seasonal or annual) storage. Latent TES is used primarily for short term storage applications, with the exception of using seasonal storage of natural ice and snow collected during winter and used for summer cooling. On the other hand, sensible TES systems are utilized for both short- and long-term storage. Some of the media for sensible and latent TES are shown in Table 1-1.

Table 1-1: Media for short- and long-term TES systems, (Dincer & Rosen 2011)

Sensible thermal energy storage		***Latent thermal energy storage***	
Short-term	*Long-term*	*Short-term*	*Long-term*
-	Rock & Earth beds	Inorganic materials	-
Concrete, Bricks, etc.	-	Organic materials	-
Water tanks	Large water tanks	Fatty acids	-
-	Aquifers	Aromatics	-
-	Solar ponds	Water-ice (artificial)	Natural ice and snow

Sanner et al. (1998) and Nordell (2000) specify additional parameters for classification of TES systems: according to storage purpose (heating, cooling, and combined heating and cooling); storage temperature (low < 40-50°C or high > 50°C); storage technology (aquifer TES, borehole TES, pit-tank TES, PCMs, etc.); and storage application (residential, commercial, or industrial).

A variety of TES techniques for space heating and space cooling, have developed over the past decades. The content of this study deals in details with the following concepts: seasonal TES in the ground; building thermal mass utilization for diurnal TES; and use of Phase Change Materials (PCMs) in building materials and components for enhancing building's thermal mass.

The present study on TES for heating and cooling applications is oriented towards zero emission buildings design. However, insight into past applications as well as energy needs according to present building codes is given as a start point for further development and design according to future energy needs.

2. Objectives

The main objectives of the PhD Thesis are to:

- Investigate intelligent TES possibilities for heating and cooling applications in buildings including seasonal ground storage, building thermal mass utilization, and phase change materials for building's thermal mass enhancement;
- Investigate the possibility of using PCMs in building materials and components for increasing building thermal mass;
- Identify and discuss the PCM enhanced thermal mass properties;
- Identify and discuss the main parameters influencing the efficiency of PCM enhanced thermal mass;
- Identify and discuss barriers for utilizing PCM for thermal mass enhancement;

The thesis uses searches in the literature and experimental and analytical assessment.

3. Outline of the thesis

The thesis constitutes five main parts which, excluding the first introductory part, are:

PART II includes literature review study on thermal energy storage in buildings, including seasonal storage in the ground, short term storage in building's thermal mass, and use of phase change materials for building thermal mass enhancement. The review on seasonal thermal energy storage in the ground formed the basis of Paper I, *'Thermal energy storage –A review of concepts and systems for heating and cooling applications in buildings: Part I – Seasonal storage in the ground'*, which is enclosed in Appendix A.

PART III is a parametric study, employing a computer simulation model. In this part the efficiency and potential benefits of the use of PCM-gypsum ceiling panels to enhance the thermal mass of lightweight office buildings and to improve cooling load management is evaluated. The effects of several parameters are studied on the efficiency of added by the PCM thermal mass for a 2-persons office cell. The work presented in Part III was partly utilized in forming the basis for the development of Paper II *('Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels'*) and Paper III *('Use of PCM-Plasterboard Ceiling Panels for Building Thermal Mass Enhancement, Temperature Control and Peak Load Management in a Continental Mediterranean Climate'*), enclosed in Appendix A.

PART IV is an experimental study in which the performance of ceiling panels with PCM, in terms of temperature control and cooling load management, for a typical office environment, is evaluated through a series of experimental case studies in a climate chamber. The results from the experimental study are compared with the results from a computer simulation model, in order to evaluate of the accuracy the predicted behavior of PCM ceiling panels through computer simulations.

PART V aims at summarizing the different findings from all parts and papers in this thesis. Discussion on the main findings and final conclusions from the work as a whole are presented.

PART II: LITERATURE STUDY

The chapters in this part will summarize work on the subject of thermal energy storage in and around buildings found in literature. The different concepts as well as important parameters afecting the performance of short and long term thermal energy storage systems will be presented and discussed.

Chapter 4 will present a brief literatire review study on seasonal thermal energy storage in the ground. More detailed review on the concept is given in Paper I, 'Thermal energy storage –A review of concepts and systems for heating and cooling applications in buildings: Part I – Seasonal storage in the ground', enclosed in Appendix A.

Chapter 5 will present a review study on passive and active building thermal mass utilization possibilities, for room temperature control and heating and cooling load management in buildings.

Chapter 6 summarizes work found in literature on the potential use of PCMs in building materials and components for thermal mass enhancement in lightweight buildings and during retrofitting.

4. Seasonal Thermal Energy Storage in the Ground

One of the main issues impeding the utilization of the full potential of natural and renewable energy sources, e.g., solar and geothermal, for space heating and space cooling applications is the development of economically competitive and reliable means for seasonal storage of thermal energy. This is particularly true at locations where seasonal variations of solar radiation are significant and/or in climates where seasonally varying space heating and cooling loads dominate energy consumption.

The interest in large-scale seasonal thermal energy storage started with the oil crisis in the early seventies. The objectives of such systems are either to store solar heat collected in summer for space heating in winter, or to provide heating and cooling by storing heat underground in summer and removing heat in winter. In winter, a ground source heat pump (GSHP) extracts heat from the thermal storage and in summer it extracts heat from the building to store it in the ground. These systems contribute significantly to improving the energy efficiency and reducing the greenhouse gas emissions to the atmosphere.

This chapter attempts to summarize developments during the last four decades in seasonal TES in the ground, using different storage concepts and utilizing different natural and renewable energy sources. The aim is to provide the basis for development of new intelligent seasonal TES possibilities for use in combination with space heating and space cooling applications.

4.1 Underground Thermal Energy Storage (UTES) Concepts

The principle methods available for seasonal storage of thermal energy mostly store energy in the form of sensible heat. Storage of sensible heat is influenced by energy losses during the storage time. These losses are function of storage time, storage temperature, storage volume, storage geometry, and thermal properties of the storage medium. Since seasonal thermal energy storage requires large inexpensive storage volumes, due to the large storage timescales, the most promising technologies were found in the ground, where the ground temperatures vary much less than the ambient temperature. Such systems are called underground thermal energy storage (UTES) systems (Nordell 2000). Among the UTES systems developed since 1970s, the ongoing engineering research focused mainly on four types of storages: water tank, water-gravel pit, aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), Figure 4-1. In Table 4-1: are summarized the characteristics of the main underground seasonal storage concepts.

Water tank thermal energy storage consists of a reinforced concrete tank buried in the ground, which can be built nearly independently of geological conditions. It is thermally insulated at least on the roof area and on the vertical walls. Steel liners are introduced in the structure to guarantee water tightness and to reduce thermal losses caused by vapor transport through the walls (Schmidt et al. 2004). Due to high specific heat of water and the possibility for high capacity rates for charging and discharging, this technology is the most favorable from a thermodynamic point of view.

Gravel-water pits consist of a mix of gravel and water and are normally buried in the ground. They need to be waterproofed and insulated at least at the side walls and on the top (Schmidt et al. 2004). Thermal energy is charged into and discharged out of the storage either by direct water exchange or by a heat exchanger based on plastic piping installed in different layers inside the storage. The gravel-water mixture has lower specific heat capacity than water alone and for this reason the volume of the whole basin has to be higher compared to water tank storage to obtain the same thermal storage capacity.

Table 4-1: Comparison of storage concepts (Schmidt et al. 2003, Novo et al. 2010)

Storage concept	***Water tank***	***Gravel-water pit***	***Aquifer***	***Borehole***
Storage medium	*Water*	*gravel-water*	*sand/water-gravel*	*soil/rock*
Thermal capacity, kWh/m^3	60-80	30-50	30-40	15-30
Storage volume for 1 m^3 water equivalent	1m^3	1.3-2m^3	2-3 m^3	3-5 m^3
Geological requirements	- Stable ground conditions - Preferably no ground water - 5-15m deep	- Stable ground conditions - Preferably no ground water - 5-15m deep	- Natural aquifer layer with high hydraulic conductivity - No or low natural ground water flow - Suitable water chemistry at high temperatures - 20-50m deep	- Drillable ground - High heat capacity - High thermal conductivity - Low hydraulic conductivity - Natural ground water flow < 20 m/year - 30-200m deep
Application (H - heating; C - cooling)	H - CSHPSS	H - CSHPSS	H - CSHPSS H & C - GSHP	H - CSHPSS H & C - GSHP

Aquifers are below-ground widely distributed sand, gravel, sandstone or limestone layers with high hydraulic conductivity which are filled with groundwater (Schmidt et al. 2004). If there are impervious layers above and below and no or low natural groundwater flow, they can be used for thermal storage. In this case, groups of wells are drilled into the aquifer and serve for extraction or injection of groundwater. During charging periods cold groundwater is extracted from the cold well, heated up by the heat source and injected into the hot well. In discharging-periods the flow direction is reversed: warm water is extracted from the warm well, cooled down by the heat sink and injected into the cold well. Due to the different flow directions both wells are equipped with pumps, production- and injection pipes. Because the storage volume of an ATES cannot be thermally insulated against the surroundings heat storage at high temperatures (above 50°C) is normally only efficient for large storage volumes (more than 20000 m³) with a favorable surface to volume ratio. For low temperature or cooling applications also smaller storages can be feasible. Especially for high temperature thermal storage a good knowledge of the mineralogy, geochemistry and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling, etc.

In borehole thermal energy storage, thermal energy is directly stored in the ground. Suitable geological formations are e.g. rock or water-saturated soils (Schmidt et al. 2004). U-pipes, so called ground heat exchangers, are inserted into vertical boreholes, into a depth of 30-200 m, to build a huge heat exchanger. The boreholes are usually filled with groundwater, or with bentonite, quartz sand or thermally enhanced grouts. While water is running in the U-pipes heat can be fed in or out of the ground. The heated ground volume comprises the volume of the storage. At the top of the storage usually there is a heat insulation layer to reduce thermal losses to the surface.

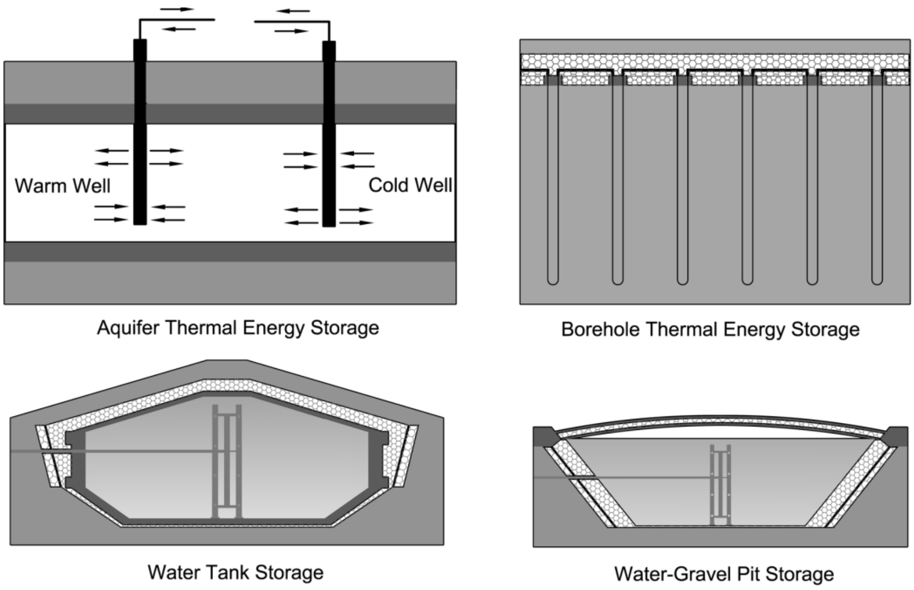


Figure 4-1: Underground Thermal Energy Storage Concepts

Depending on the application of-, and the heating/cooling demand on the storage, different design requirements for borehole configuration and groundwater flow may apply. For solar-thermal applications, due to the need for seasonal storage of solar heat, minimized heat exchange between the BTES and surrounding ground is desired. Therefore, rectangular or circular configuration (with high volume to surface area ratio) of the storage and low natural groundwater flow are prerequisites for design. For GSHP applications, the requirements for the configuration of the boreholes are set by the share of the heating and cooling of the total energy need of the building. For example, if there is a cooling dominated situation, the heat rejection to the ground in summertime will be higher than the heat extraction from the ground in winter. Due to that imbalance in the ground loop, the ground temperature will increase. The increasing of the ground temperature will reduce the efficiency of the GSHP system in the summer. The vice versa situation will be observed in a heating dominated situation. In these cases, the heat exchange area between the borehole system and surrounding ground should be maximized, in order to avoid heat accumulation or depression in the borehole field. That would make linear borehole configuration more beneficial. Additionally, high groundwater flow would enhance the dissipation of thermal energy in the surrounding ground, thus improving system performance. For balanced annual heating and cooling loads, the GSHP-BTES system would benefit from using the ground system for seasonal storage of heat or cool, and the design prerequisites for solar-thermal system will apply.

BTES do not have vertical but horizontal temperature stratification from the center to the borders. This is because the heat transfer is driven by heat conduction and not by convection. At the boundaries there is a temperature decrease as a result of the heat losses to the surroundings. When rectangular or circular storage is designed, the horizontal stratification is supported by connecting the supply pipes in the center of the storage and the return pipes at the boundaries. During charging, the flow direction is from the center to the boundaries of the storage to obtain high temperatures in the center and lower ones at the boundaries of the storage. During discharging the flow direction is reversed.

One advantage of this type of storage is the possibility for a modular design. Additional boreholes can be connected easily and the store can grow with e.g. the size of a housing district. The size of the storage should be three to five times higher than that of water tank storage to obtain the same thermal capacity. **Table 1-1**Table 4-2 shows typical general values for BTES systems.

Table 4-2: Typical values of BTES systems for heat storage applications (source: http://www.highcombi.eu)

Borehole diameter	0.1-0.15 m	Flowrate in U-pipes	0.5-1.0 m/s
Borehole depth	30-200 m	Ave. capacity/m borehole	20-30W/m
Distance b/n boreholes	2-4 m	Min./max. inlet temperature	-5/+90°C
Ground thermal cond.	2-4 W/(mK)	Cost of BTES/m borehole	50-80 €/m

4.2 Design Guidelines for Underground Thermal Energy Storages

For the construction of ground buried thermal energy storages, like water tanks and water-gravel pit storages, there are no standard procedures regarding wall construction, charging device, and geometry (e.g. surface-to-volume ration), available. Due to the size and geometry and also due to the requirements in terms of leakage detection and lifetime most techniques and materials have their origin in landfill construction. However, with respect to high operation temperature, materials and techniques cannot be simply transferred. Design recommendations for construction of water-tank and water-gravel pit storages are given in HIGH-COMBI Report (2008).

General demands and recommendations for the design of ATES and BTES systems can be found in the VDI (Verein Deutscher Ingenieure - Association of German Engineers) “Guideline VDI 4640: Thermal use of the Underground”, parts 1-4. The guidelines concern the thermal use of the ground to a depth of about 400 m. Systems for heating only, cooling only and both heating and cooling are treated in the first part. Environmental aspects such as primary energy use, CO_2 emissions, thermal impacts on the ground and groundwater, hydraulic impacts, possible consequences of leakage of heat carrier fluids are included as well. The second part includes design guidelines for the possible specific heat extraction rate for ground-coupled heat pumps with vertical boreholes or shallow horizontal pipes. In the third part, storage specific aspects like e.g. water treatment methods to prevent precipitation caused by chemical changes and suitable materials for different applications (temperatures) are mentioned. ATES and BTES systems are described in detail including hydro-geological prerequisites and recommendations for design. Part four focuses on the direct usage of underground cold or heat without any additional equipment like groundwater cooling or heating.

Additional information for ground source cooling systems with thermal energy storage, utilizing ATES and BTES concepts, is given in a pre-design guide developed by Hummelshøj (2004).

4.3 Seasonal Storage of Solar Thermal Energy for Heating Applications

Seasonal storage of solar thermal energy for space heating purposes has been under investigation in Europe since the mid-1970s within large-scale solar heating projects. Most large-scale solar systems have been built in Sweden, Denmark, The Netherlands, Germany and Austria (Dalenbäck 2007). The first demonstration plants were developed in Sweden in 1978/1979, based on results from a national research programme (Dalenbäck et al. 1985). In the past two decades, the main activities have been within the work initiated in the IEA ‘‘Solar Heating and Cooling” programme Task VII ‘‘Central Solar Heating Plants with Seasonal Storage (CSHPSS)”, the work carried out in Europe within the EU/APAS-project ‘‘Large-Scale Solar Heating Systems” (Fisch et al. 1998), as well as the German R&D programmes Solarthermie-2000 and Solarthermie-2000plus (Lottner et al. 2000, Schmidt et al. 2004, Bauer et al. 2010).

So far, the development of seasonal storage has been aimed at heating large district system stores part of CSHPSS in order to fulfill technical viability and cost effectiveness by using large storage volumes. Figure 4-2 shows a scheme of a CSHPSS (distributed rooftop solar collectors, central plant with heat pump, solar collectors and heat distribution networks).

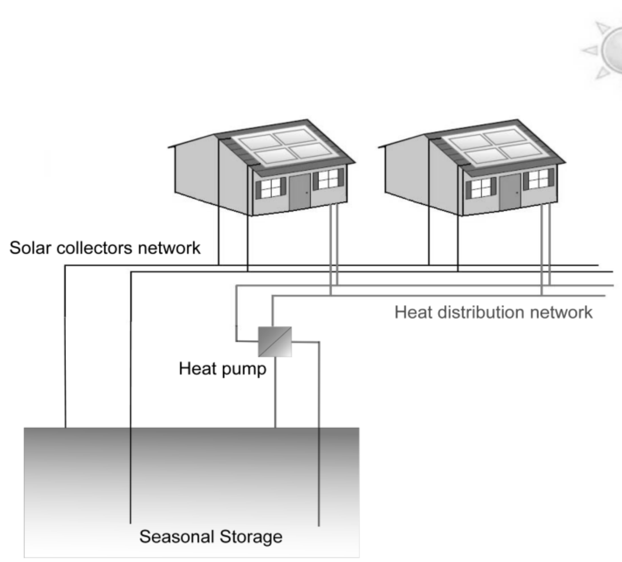


Figure 4-2: Scheme of a Central Solar Heating Plant with Seasonal Storage

Fisch et al. (1998) reviewed large scale solar plant development in Europe during the 1990s. The work refers to two large-scale solar heating applications: systems with short-term (diurnal) storage designed to supply 10–20% of the annual heating demand or 50% of the domestic hot water; and systems with long-term (seasonal) storage capable of supplying 50–70% of the annual heating demand. Within the findings of that work was that large-scale solar applications benefit from the effect of scale. Compared to small solar domestic hot water systems, the solar heat cost can be cut at least in third. Among the main results of the evaluation of the existing projects was the need to reduce the cost-benefit ratio for CSHPSS.

Seasonal heat storage for solar thermal applications needs large volumes of storage to supply the energy stored during summertime along winter. Those large storages require the development of technologies capable of minimizing heat losses in order to preserve the thermal performance and life time of the solar heating plant. These approaches must be coupled with low investment, at least lower than conventional heating and cooling systems.

Four different seasonal heat storage types for solar thermal applications have been investigated in this review chapter: water tank storage, water-gravel pit storage, borehole thermal energy storage (BTES), and aquifer thermal energy storage (ATES). The selection of a specific storage type depends on the geological and geo-hydrological situation in the ground at the respective construction site. A preliminary geological and geo-hydrological examination of the site is recommended which can be expensive and time consuming. Ford & Wong (2010) have studied the above mentioned phenomena, and have presented regional models for screening potential underground areas for ATES and BTES systems implementation. The findings are based both on geological data and output from a three-dimensional groundwater flow model MODFLOW (McDonald & Harbaugh, 1988).

4.3.1 Pilot Projects for CSHPSS

Table 4-3 summarizes the technical characteristics of some demonstration plants in central solar heating systems with water tank, gravel-water pit, borehole, and aquifer storage. The experimental projects have been selected as they are large-scale pilot plants. An overview of the effectiveness of the diverse configurations of these systems, including solar heat systems costs, is provided. The given numbers for the solar fraction of total heat delivered are simulated values for long-term operation.

Experiences from the different pilot projects show that water tank thermal energy storages are technically feasible and work well. However, construction costs and thermal losses are still too high (Kübler et al. 1997). Considerable cost reductions can be obtained with the development of high-density concrete materials, which would allow the omission of the use of expensive steel liners for the storage construction (Schmidt et al. 2004). Problems with high thermal losses due to wet thermal insulation have revealed the importance of water tank insulation for the long-term performance of CSHPSS (Dalenbäck et al. 1985). Advances in stratification devices and heat insulation can lower significantly the construction costs (Schmidt et al. 2006).

Experiences with the gravel-water pit storage have shown that sealing of the pit, insulation and ground works account for significant part of the costs (Schmidt et al. 2004, Pfiel et al. 2000, Heller 2000). Moisture protection of the insulation is important for the thermal performance of the concept. In addition, the seasonal gravel-water pit storages have shown difficulties to make it sufficiently tight and to localize and repair leakages. Research for developing cost effective solutions is needed. Further studies, regarding system thermal performance relative to the use of direct and indirect heat exchangers, are necessary.

Table 4-3: Technical data of CSHPSS

CSHPSS with storage type	Heated living area	Tot. heat demand, GJ/a	Solar collector area, m^2	Storage volume, m^3	Solar frac., %	Max. design storage temp., °C	Sol. heat cost analysis date, MWh	References
Water tank								
Hamburg, DE	14800 m^2	5796	3000	4500	49*	95	256 EUR	Kübler et al. 1997; Schmidt et al. 2004; Lottner 2000; Bauer 2010
Friedricshafen, DE	39500 m^2	14782	5600	12000	47*	95	158 EUR	Kübler et al. 1997; Schmidt et al. 2004; Lottner 2000; Bauer 2010
Hannover, DE	7365 m^2	2498	1350	2750	39*	95	414 EUR	Schmidt et al. 2004; Lottner 2000; Bauer 2010
Munich, DE	300 apt.	8280	2900	5700	47*	95	240 EUR	Schmidt et al. 2006; Bauer 2010
Ingelstad, SE	52 houses		1320	5000	14*		1900 SEK	Dalenbäck et al. 1985
Lambohov, SE	55 houses		2700	10000	37*		1100 SEK	Dalenbäck et al. 1985
Hoerby, DK				500				Heller 2000
Herlev, DK		4520	1025	3000	35*			Heller 2000
Gravel-water pit								
Stuttgart, DE		360	211	1050	60*	85		Hahne 2000
Chemnitz, DE	4680 m^2	4320	2000	8000	42*	85	240 EUR	Schmidt et al. 2004
Steinfurt, DE	3800 m^2	1170	510	1500	34*	90	424 EUR	Pfiel et al. 2000
Eggenstein, DE	12000 m^2	3276	1600	4500	40*	80		Bauer et al. 2010
Ottrupgaard, DK		1630	560	1500	16*			Heller 2000
BTES								
Neckarsulm, DE	20000 m^2	1663	5000	63400	50*	85	172 EUR	Nußbicker et al. 2003; Schmidt et al. 2004; Bauer et al. 2010
Crailsheim, DE	260 houses	14760	7300	37500	50*	85	190 EUR	Mangold 2007
Attenkirchen, DE	6200 m^2	1753	800	10000	55*	85	170 EUR	Schmidt et al. 2004
Anneberg, SE	9000 m^2	3888	3000	60000	60*	45	1000 SEK	Nordell et al. 2000; Lundh et al. 2008
Okotoks, CA	52 houses	1900	2293	35000	90*	80		McDowell & Thornton 2008; Sibbit et al. 2007; Chapuis & Bernier 2009
ATES								
Rostock, DE	7000 m^2	1789	1000	20000	62*	50	255 EUR	Schmidt et al. 2000; Schmidt et al. 2004; Lottner 2000; Bauer 2010

CA = Canada, DE = Germany, DK = Denmark, SE = Sweden; * Calculated values for long-time operation.

For BTES, the experiences with CSHPSS show that the major investment for the solar plant is the cost of building the storage; e.g. drilling of boreholes, construction of heat exchangers, refill of boreholes (Nußbicker et al. 2003, Bauer et al. 2010, Mangold 2007, Nordell et al. 2000, Lundh et al. 2008) In addition to storage design, due to the low heat transfer rates between circulating fluid and ground, these systems have shown dependence on the development of buffer storage techniques. Buffer storage hot water tanks are often added to the system in order to manage the high capacity rates of the solar collectors during summertime and the high demand rates for heating during wintertime.

Well construction is the predominant part of the costs for aquifer thermal storages. In reality, depending on site specific conditions, several serious problems have to be solved, e.g., clogging of wells, scaling of the external heat exchangers, necessity of water treatment, and high heat losses especially in small aquifer storage projects (Lottner et al. 2000, Schmidt et al. 2004, Bauer et al. 2010).

4.3.2 Operational Experiences and Design Considerations for CSHPSS

The operational characteristics of the different CSHPSS, presented in Table 4-3, are based on simulated values for long term performance of the solar plants. In Bauer et al. (2010), three different seasonal thermal energy storages have been tested and monitored under realistic operating conditions: Friedrichshafen (water tank), Neckarsulm (boreholes), and Rostock (aquifer). Their operational characteristics are compared using measured data from an extensive monitoring program. The long term operational experiences are shown.

The results from the monitoring campaigns at the different solar plants have shown that, in order to achieve high solar energy efficiency, the solar plants have to be operated at low temperatures. Low storage temperature limits heat losses and improves solar collector efficiencies. Suitable techniques for fully benefitting from such low temperature systems are to use low-temperature heating systems (typical range: 25-35°C)) like floor heating in the buildings. In contrast for high temperature systems (e.g. radiators) the seasonal storage must be built in a much bigger scale than for low temperature systems because of the higher storage heat losses.

For seasonal storage, low temperature concepts with the use of heat pumps to raise the temperature of the water used for space heating to a suitable level is an appropriate option. This technology, conceptually and practically implemented in the plants in Rostock, Eggenstein and Crailsheim (Lottner et al. 2000, Schmidt et al. 2004, Bauer et al. 2010) and in conceptual phase for the plant in Okotoks (Chapuis and Bernier 2009), enables the utilization of the full potential of solar heating plants with seasonal storage. Using a heat pump to discharge the seasonal storage to lower temperatures allows higher usability and increased storage capacity and storage efficiency. The solar plant becomes more robust against high return temperatures of the heat distribution net and solar collectors net, which allows to reduce the solar collector area required, increase the solar collectors' efficiency, and obtain high solar fractions (based on total heating demand).

The solar fraction of the delivered heat is not the only parameter that can be used for performance assessment of central solar heating plants with seasonal storage. In addition, the efficiency of solar assisted district heating systems can be evaluated by the amount of solar heat per m^2 collector area delivered into the district heating net. Even though this parameter is dependent on local site conditions, like irradiation on the collector pane, it could give insight into any advantages or disadvantages of using different storage concepts. The monitoring results from the different plants shown in Bauer et al. (2010) do not show any clear tendencies in favor of or against a certain storage concept.

In addition, the above discussed parameter could give some design prerequisites regarding solar collectors' area and storage volume. Different methods for determining the optimal size of collector area and storage volume for seasonal storage of solar heat have been developed. Braun et al. (1981) described a methodology for the design of these systems using the simulation program TRNSYS (Klein 2004). Significant reduction in the collector area has been achieved by use of seasonal storage. It has been shown that the trade-offs between collector area and storage volume requirements, for a fixed system performance, are location dependent. Greater reductions in collector area requirements with increasing storage capacity occur in northern latitudes (valid for the northern hemisphere). Simillar results have been confirmed from the demonstration plants studied by Lottner et al. (2000), Schmidt et al. (2004) and Bauer et al. (2010). However, no clear guidelines or design recommendations have been developed.

The seasonal energy storage technologies for solar energy applications are characterized by many factors such as solar collectors, annual sun exposure, heat distribution networks, heat demand and insulation of the buildings, and the seasonal thermal storage requirements. Once these technologies have been well developed, the main effort consists in reducing costs in order to make them market competitive against conventional energy sources.

As some authors suggest, the specific storage costs are related to water equivalent storage volume. The water equivalent is the corresponding water volume to store the same amount of heat. Experiences carried out in demonstration plants have achieved cost reduction by increasing the storage volume in large-scale solar applications. Figure 4-3 presents the cost data of some pilot and demonstration plants reviewed in this Chapter. The strong cost reduction with an increasing storage volume is obvious. Appropriate sizes for seasonal heat storage are located between 2000-20000 m^3 water equivalent. Within this range the investment costs vary between 40-250 Euro/m^3. Generally, water tank storage is the most expensive concept. On the other hand, it has some advantages concerning the thermodynamic behavior and it can be built almost independently of the geo-hydrological site conditions. The lowest costs can be reached with ATES and BTES. However, they have the highest requirements on the local ground conditions.

The economy of CSHPSS depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Before starting the design of a new plant, geological conditions of the location, characteristics of the heat source and demands of the consumers have to be analyzed thoroughly. Important parameters are maximum and minimum operating temperatures of the storage and heat distribution system. Optimal size of solar collector area and seasonal storage volume are of vital importance.

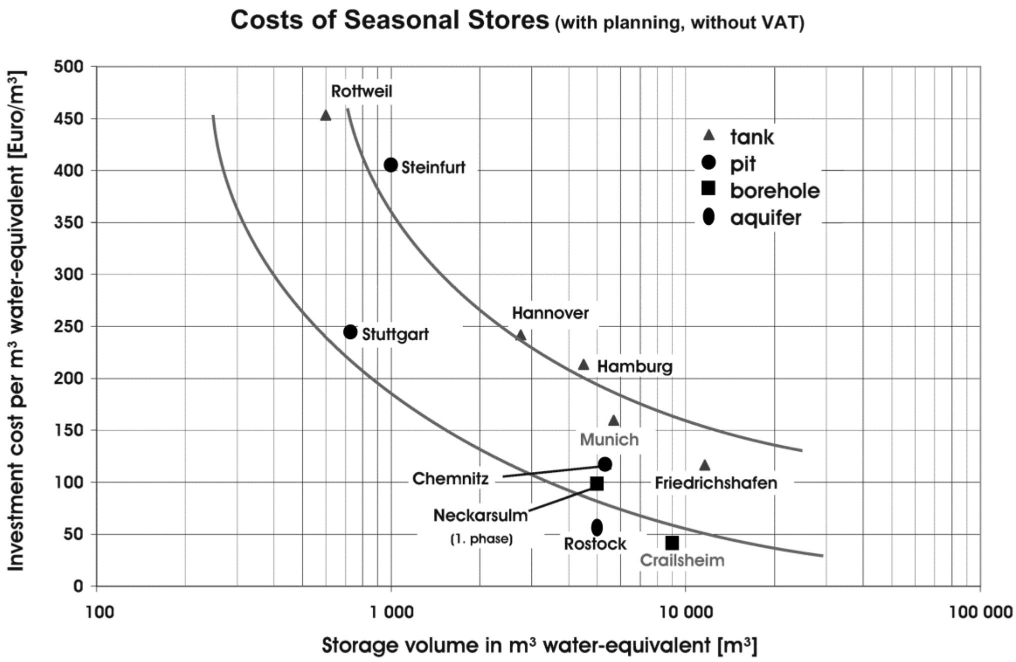


Figure 4-3: Cost of Seasonal Stores for CSHPSS (Lottner et al. 2000; Schmidt et al. 2004; Mangold 2007).

To determine the economy of a storage, the investment and maintenance costs of the storage have to be related to its thermal performance (the cost of the usable stored energy). If the geo-hydrological site conditions make different storage types feasible, an economic optimization via system simulations should be conducted by taking the construction costs of the different concepts into account. Among the developed dynamic simulation tools capable of determining the technical feasibility and cost-effectiveness of central solar heating plants with seasonal storage could be mentioned SOLCHIPS (Lund 1992, 1997), MINSUN (Mazzarella 1990) and TRNSYS (Klein 2004).

The findings from computer simulation studies and monitoring campaigns show that, although widely used in some countries, the concept of CSHPSS requires further research in order to make it economically competitive with conventional energy sources. More studies, related to cost reductions for construction of the storage; heat insulation and reduction of storage heat losses; operating temperatures of the storage, solar collectors net and heat distribution net in regards to efficiently utilizing the low-temperature concept with the use of heat pumps; efficiency of solar collectors; optimal solar collector area and seasonal storage volume; coupling between solar plant and low-temperature heating systems, are needed.

4.4 Underground Thermal Energy Storage with Ground Source Heat Pumps

Underground Thermal Energy Storage (UTES) systems with Ground Source Heat Pumps (GSHPs) use the underground for exchange of thermal energy for efficient heating and cooling of buildings. The application is based on the natural ground temperature. The GSHP extracts heat from the ground in winter and injects heat in summer. The GSHP technology offers higher energy efficiency for air-conditioning compared to conventional air conditioning systems because the underground environment provides lower temperature for cooling and higher temperature for heating and experiences less temperature fluctuation than ambient air temperature change. These result in high COP (coefficient of performance) of the heat pump in both heating and cooling mode.

The development of UTES is strongly supported within the framework of the International Energy Agency (IEA). The IEA Energy Storage Annex 8 is the focal point for all activities related to UTES. Underground heat storage in the temperature range below 40°C is usually done to increase the heat-source temperature of heat pumps. High-temperature UTES systems have storage temperatures above 40°C to 50°C. Heat pumps are either used at the end of the storage unloading period, when temperatures drop, or for achieving higher supply temperatures. With increasing temperatures, hydrochemical, biological and geotechnical problems increase. Annex 12 of the IEA programme on Energy Conservation through Energy Storage (IEA ECES) addresses the specific problems of high temperature UTES.

Cold storage systems with heat pumps have been under investigation by the IEA for many years. Typical modes of operation of such systems are direct cooling in spring and during low demand periods, and cooling by heat pump in summer or during peak demand periods. These systems substitute chillers which, compared to thermal storage, have a relatively high energy demand. Seasonal cold storage is now commercialized in some countries. A database made under IEA ECES Annex 7 lists approximately 90 realized projects in the four participating countries (Canada, Germany, the Netherlands, Sweden). Forty of these projects include heat pumps. The size and capacity of cold UTES varies widely. A trend towards very large systems can be seen.

GSHP and UTES systems are applied in various European countries and North America. While, in some countries these systems are already considered as a standard design option for heating and cooling, in others the technology is quite recent. Rybach et al. (2000) describes the technologies, the market situation, future trends and questions related to GSHP systems development in Europe. A world overview of geothermal heat pumps development and utilization is presented by Lund et al. (2004). Status development and applications in United States and Europe are investigated. Insight into system's efficiency, particularly heat pump COPs in heating and cooling mode, is given.

In general two types of UTES, for combined heating and cooling applications, can be distinguished: aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) (Nordell 2000). As discussed in the section for seasonal storage of solar energy, for geological or geo-hydrological reasons it is not possible to construct these systems at any location.

An ATES system is a large open-loop system optimized and operated to realize seasonal thermal energy storage. The principle is shown in Figure 4-4. In summer, groundwater is extracted from the cold well and used for cooling purposes. The warmed up water is injected in the warm well. In winter the process is reversed. Water is pumped from the warm well and applied as a heat source, e.g. as low temperature heat source for a heat pump. The chilled groundwater is then injected into the cold well again. With ATES all the water extracted from one well is re-injected in another well. This means that there is no net extraction of groundwater from the soil, which minimizes negative impacts on the environment.

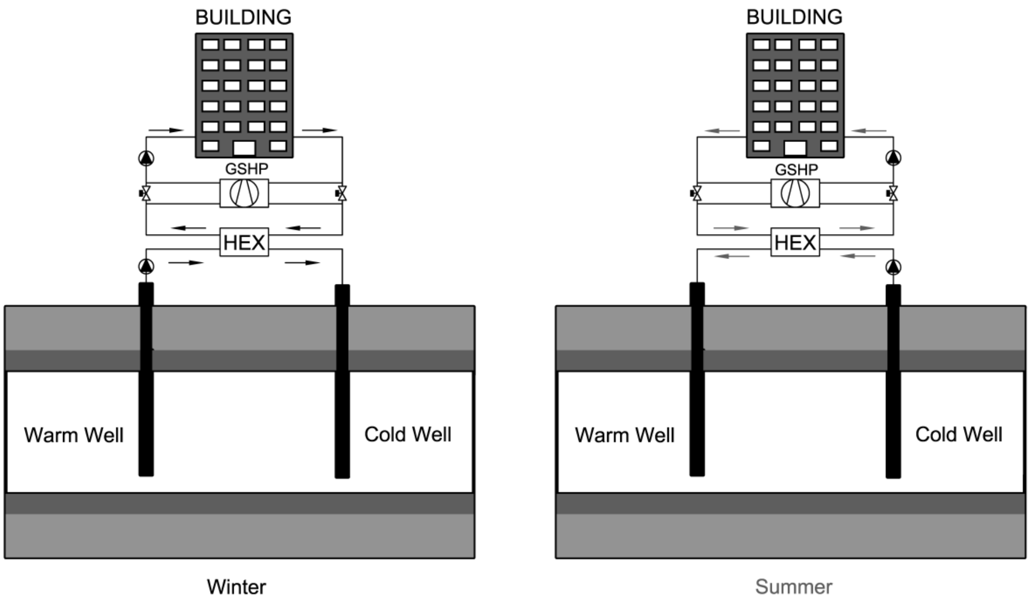


Figure 4-4: GSHP with Aquifer seasonal storage

A BTES system consists of a number of closely spaced boreholes. The principle is shown in Figure 4-5. During the heating season the borehole heat exchanger is used for extraction of heat from the ground, which service as a heat source for the heat pump. While the circuit water passes through the heat pump its temperature cools down. The chilled water is returned in the borehole heat exchanger and the ‘cold-energy’ is stored in the ground. During the cooling season the flow in the BTES system is reversed. The stored cooling energy is extracted and passed through a heat exchanger providing direct cooling to the building. In periods of peak cooling demand the (reversible) heat pump can be used. The circuit water will pick up energy from the building and thus be raised in temperature. It will be returned in the borehole heat exchanger where the ‘warm energy’ is stored in the ground for the next heating season.

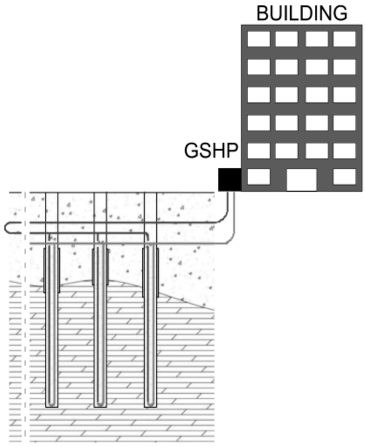


Figure 4-5: GSHP with Borehole seasonal storage

4.4.1 Pilot Projects for UTES with GSHPs

In Table 4-4 are summarized some technical data of pilot projects with ground-source heat pumps utilizing aquifer or borehole seasonal storage concepts.

ATES systems require that relatively high well yields can be obtained on site. Because of this the applicability depends strongly on site-specific hydrogeological conditions. An advantage of such systems is the generally higher heat transfer capacity of a well compared to a borehole. This makes ATES usually the cheapest alternative if the subsurface is hydro-geologically and hydro-chemically suited for the system.

Closed-loop BTES systems depend less on site-specific hydro-geologic conditions than ATES systems and are better suited for areas where relatively high well yields are not obtainable. In addition, since the systems are operated in closed loop (i.e., there is no contact between natural ground water and the heat exchange fluid), they have potential to find much wider application compared to ATES. A disadvantage of this concept is the relatively high construction cost, mainly due to drilling.

Table 4-4: Technical data of ground-source heat pump systems with aquifer seasonal thermal energy storage

	Total building area, m^2	System purpose		System capacity, MW		Energy delivery, GWh/a		Savings		References
		heating	cooling	heating	cooling	heating	cooling	El. reduc.	CO_2 reduction	
GSHP with ATES										
Eindhoven (TUe), NL	250000	+	+	20	20	25-33	25-30	20%*	20%*	Snijders et al. 2003
Berlin (Parliament), DE	-	+	+	-	-	2.05	3.95	-	-	Sanner et al. 2005
Malmo, SE	-	-	+	-	1.3	-	3.9	-	-	Anderson et al. 2003 Anderson 2007c
Stockholm, SE	-	-	+	-	25	-	0.9	-	-	Andersson & Rudling 2000; Andersson 2007b
Gardermoen Airport, NO	-	-	+	-	8	-	13	-	-	Eggen & Vangsnes 2005
Louisville, Kentucky, US	161651	+	+	19.6	15.8	-	-	47%*	47%*	Lund et al. 2004
PARC, Agassiz, CA	7000	+	+	0.3	0.56	-	-	-	-	Bridger & Allen 2010
Medicine Hat, CA**	12000	+	+	1.8	1.1	2.7	1.1	-	480 ton/a	Wong et al. 2006
GSHP with BTES										
Stockholm, SE	-	-	+	-	0.22	-	-	40%*	40%*	Rybach & Sanner 2000
Lund, SE	4200	+	+	0.3	0.3	0.395	0.15	-	-	Andersson 2007d
Falstadsenteret, NO	2850	+	+	0.13	0.13	-	-	-	-	Midttømme et al 2008
EANDIS, BE	16363	+	+	1.9	1.2	0.9	0.824	31%*	31%*	Desmedt et al. 2008 Desmedt et al. 2010
UOIT, CA	80000	+	+	1.4	1.3	-	-	40%h*16%c*		Dincer & Rosen 2011
Langen, DE	44500	+	+	0.33	0.34	0.07	0.06	77%*	77%*	Sanner et al. 2003

BE = Belgium; DE = Germany; NL = Nederlands; NO = Norway; SE = Sweden; US = United States

* Savings compared to conventional systems supplying the system loads and services

** Pilot project under development

4.4.2 Operational Experiences and Design Considerations for UTES with GSHPs

The use of ground-coupled systems in buildings offers economic as well as environmental advantages. When both heating and cooling is required, a ground-coupled system can function both as a heat source and a heat sink. These double-effect storage projects are more likely to be economical.

Experiences from ATES pilot projects and demonstration plants show storage efficiencies of 60 to 90% (Sanner et al. 2005, Andersson 2007b, Andersson 2007c). Primary energy savings and CO_2 emission reductions vary from 20 to 47%, in the different projects (Snijders 2003, Lund et al. 2004). These systems show high potential for free cooling operation, which concept has been widely utilized in the projects discussed in this paper. For heating purposes, temperature upgrade by heat pumps is needed.

Experiences from BTES pilot projects and demonstration plants have shown primary energy savings and CO_2 emission reductions from 16 to 40%, in the different projects (Fellin & Sommer 2003, Rybach & Sanner 2000, Desmeth et al. 2008, Desmeth et al. 2010, Dincer & Rosen 2011). Estimated payback periods for the different projects have resulted in 8 to 12 years. Compared to systems with ATES, BTES systems show less potential for free cooling operation, mainly for some period at the beginning of the cooling season. Due to the low heat transfer rates between borehole heat carrier fluid and surrounding ground, and heat up of the storage, reverse heat pump operation mode is used to supplement cooling operation. For heating purposes, the ground storage is supplying low temperature heat to heat pump evaporators.

GSHP projects with ATES and BTES have high investment costs. Therefore detailed system simulation models are needed for design and dimensioning. Comprehensive thermodynamic analyses, evaluating thermal storage in aquifers for space heating and cooling, are performed by Carotenuto et al. (1990). A procedure for a numerical evaluation of the system performance and optimization is presented in a convenient form for system development and application.

Kangas et al. (1994) developed a computer model AQSYST for simulating energy systems employing ATES. The model has been used to study the application of different types of aquifers for seasonal storage of thermal energy. Simulation results suggest that high temperature storage (60-90°C) is feasible only in stagnant aquifers, whereas, for low-grade heat (15-20°C), aquifers with high natural flows can be used (500-600 m/y).

Various analytical and numerical solutions have been developed and used as design/research tools to predict the short and long term response of BTES systems. In Table 4-5 are summarized some of the most significant contributions to modelling short- and long-term response of borehole ground heat exchanger systems. The approach of Eskilson (1987) for numerical modelling of the thermal response of borehole systems, using non-dimensional thermal response functions (g-functions), is considered as the state-of-the-art and has been implemented in software like EED (Blomberg et al. 2008), TRNSYS (Claesson et al. 1981, Hellström 1989, Mazzarella 1989, Pahud 1996, Klein 2004), HVACSIM+ (Clark 1985) and GLHEPRO (Spitler 2000).

Table 4-5: Mathematical models for design and dimensioning of borehole heat exchangers

Model types	Reference
Long-term response of BTES systems	
- line source theory	Ingersoll et al. 1954
- cylindrical source theory	Ingersoll et al. 1954; Kavanaugh 1985; Bernier 2001; Bernier et al. 2004; Nagano et al. 2006
- numerical non-dim. *g-functions*	Eskilsson 1987
- analytical *g-functions*	Eskilsson 1987; Zeng et al. 2002; Lamarche & Beauchamp 2007; Bandos et al. 2009
- capacity-resistance model - *CARM*	Zarella et al. 2010
Short-term response of BTES systems	
- short time-step *g-functions*	Yavuzturk 1999; Yavuzturk & Spitler 1999, 2001; Xu & Spitler 2006
- analytical solutions for short-term response of borehole heat exchangers	Young 2001; Lamarche & Beauchamp 2007; Bandyopadhyay et al. 2008; Javed 2010
- capacity reistance model with short-term response modelling - *CARM*	Zarella et al. 2011

In order to design efficient ground-coupled systems for heating and cooling of buildings, temperature levels, surface areas of room heaters/coolers, performance characteristics of heat pumps, heat exchangers, circulation pumps, borehole geometry (aquifer characteristics), cooling/heating demand of the buildings must be taken into account to achieve an optimal system which works efficiently in economical and technical terms.

For UTES systems one of the most important external factors is the required temperature level for the heating/cooling case involved. Thermal energy storage systems become more efficient if the temperature requirement for space heating is low, about 35°C and if the temperature for cooling is high, about 15°C. In that case, low temperature difference between the store and demand side will be present and also the heat pump would operate at lower temperature difference. Proper design will result in high COP for the whole system. However, this would require the use of low-temperature heating and high-temperature cooling radiant system in the building. Thermo-active building systems (TABS) for office and commercial buildings, and floor heating/cooling systems for single- and double-family residential houses have proven successful in practice.

In Fellin & Sommer (2003) simulation analysis of an office building, equipped with a thermal slabs system, is presented. Two different climatic zones, two different strategies of ventilation, and two possibilities of plant: a traditional plant (low-temperature gas boiler and air-condensed chiller) and an innovative plant based on a GSHP, are studied. The results shows that by using a ground coupled heat pump, more than 40% of energy may be saved compared to the use of conventional system. The utilized advantages here are that the heat pump is coupled with a low-temperature heating and high-temperature cooling system (TABS), and in this particular building simulation the temperature required for slab heating in winter is only 35°C, and for slab cooling in summer 16°C are needed.

For sizing GHEs, properties like undisturbed ground temperature, ground thermal conductivity, borehole thermal resistance, specific heat capacity, are needed to deliver thermal energy at a proper temperature (Signorelli et al. 2004). The thermal efficiency of the BTES depends on the soil properties, ground water movement, temperature, and the characteristics of the thermal store itself (geometry, borehole spacing, grouting material, pipe thermal conductivity) (Gehlin & Nordell 1997, Pahud & Matthey 2001, Zeng et al. 2003, Hellström 1991, Kjellsson & Hellström 1997, Hellström et al. 1988, Lund 1985, Reuss et al. 1997).

The design of GSHP with GHEs is influenced by the heating and cooling load characteristics of the building (load pattern), the size of the ground system (depth and number of the boreholes) and the geometry of the ground system (configuration, i.e. positioning of the boreholes). The maximum and minimum design water temperature from the ground loop, and the annual heat rejection to and extraction from the ground loop are important parameters.

Naumov (2005) studied, through computer simulations with EED software, the influence of the heating and cooling load characteristics of the building (load pattern), the size of the ground system (depth and number of the boreholes) and the geometry of the ground system (configuration, i.e. positioning of the boreholes) on the overall efficiency of a GSHP system. Simulation results have shown that the brine temperature (mean brine temperature in the boreholes) differences for different borehole configurations, using the same specific borehole load (ratio between building heating and cooling needs and total borehole length), are not very large, being within 1-2 K. On the other hand, changes in the specific borehole load have a large influence on ground system performance, mean brine temperature difference of 4-8K needed for specific borehole load increased with 200-400%. Obviously, the larger the energy need of the building, the larger demand there is for the ground system and vice versa. E.g., larger demand means that the total borehole length should be larger in order to keep the mean brine temperature within required limits for heat rejection/extraction.

Furthermore, the simulations have shown that a system with balanced heating and cooling and storage (rectangular borehole layout) is more sensitive to the accuracy of the assumed load pattern than is a system for heating or cooling only (linear borehole layout). That is explainable by the fact that the requirements for the configuration of the boreholes are set by the share of the heating and cooling of the total energy need of the building. For example, if there is a heating or cooling dominated situation, then the heat exchange area of the ground system should be maximized to enhance the rejection of thermal energy in the ground and avoid heat accumulation or depression during long term operation. In that case linear borehole geometry is preferable. With a balanced heating and cooling situation however, a rectangular layout with storage capability is advantageous in terms of seasonal energy performance. However, any significant deviation from that balance (assumed load pattern) will have significant influence on the long term performance of the system (time span of 10 years considered), which has been confirmed by the simulation results. The models developed in the work of Naumov (2005), together with the design software, were applied in a case study (Astronomihuset, Lund). Simulated and measured data agreed reasonably well. Detailed results the simulation and monitoring study are presented in the given references.

Regardless of the high energy saving potential and the intensive technological development in recent years, GSHP systems with BTES wide application has been obstructed by the high investment costs associated with installing a ground loop to meet peak cooling or heating load. From another side, GSHP systems with ATES have considerably lower investment costs, but these systems are dependent on the availability of suitable natural aquifers at the site. An alternative design for ground-source systems is the hybrid system. This approach, widely considered as a variation of the ground-coupled to GHEs design, utilizes the use of a cooling towers (in cooling dominated commercial buildings) or boilers (in heating dominated residential buildings) in parallel with the GSHP system. The use of a cooling tower or a boiler allows the designer to size the ground loop for the smaller of the heating or the cooling loads, and use the GSHP in combination with the cooling tower to meet the peak cooling demand, or with the boiler to meet the peak heating demand. The hybrid equipment preserves some of the energy efficiency of the system, but reduces the capital cost associated with the ground loop installation. In addition, such a hybrid system would allow balancing the seasonal heating and cooling loads for the ground loop. The excess of building heating or cooling loads, in a heating or cooling dominated building, will be handled by the hybrid part of the system, and heat accumulation or depression in the ground system will be avoided, thus allowing design of the borehole layout in a way to benefit from seasonal storage of thermal energy.

Rafferty (1995) has evaluated, through numerical calculations, the capital costs associated with ATES, BTES, and hybrid-BTES ground-source designs, for cooling dominated commercial buildings. Specifically, the costs considered are those associated with the heat source/sink or the ground portion of the system. The heat rejection over the three designs has been standardised, assuming constant heat pump loop temperature conditions, permitting in that way a direct comparison of the three systems. Considering the same building load for the three system types, cost calculations were made for a wide variety of soil (or groundwater) temperatures, well depths (groundwater), loop lengths (ground coupled) and tower-loop ratios (hybrid system). Results show that at system capacities of 350-615 kW and above the ATES system has capital cost advantage over hybrid-BTES and the BTES systems. Below this range the hybrid system is the most attractive. Only for systems with very low capacities (less than 350 kW) and very deep aquifer depths (more than 250 m) the ATES system capital cost exceeds that of the BTES. Detailed results are given in (Rafferty 1995).

In a recent study, Hackel et al. (2011) has analyzed, through computer simulations with TRNSYS, the energetic and economic performance of three hybrid-BTES ground source heat pump installations in USA, compared to a BTES and a conventional HVAC. Two of the installations were for a cooling dominated commercial buildings located in Las Vegas (NV), and one was for a heating dominated residential building in Madison (WI). The results show that all three hybrid installations were economically cost effective. The average rate of return for investing in hybrids in these three cases has been 10% compared to a conventional HVAC system. The additional investment for a full BTES ground source system would result in an average rate of return of just 3%.

The study of Hackel et al. (2011) has shown the importance of component sizing in a hybrid system. Care should be taken not oversize the load that drives the GHE size. In addition, optimizing algorithms for proper sizing and operational modes of hybrid equipment (cooling towers and boilers) should be used. Circulation pumps use a lot of energy in a hybrid system, and due to that fact pump sizes should be minimized and the focus should be on part-load operation. Variable speed pumps should be used whenever possible. For the heat pump operation, large peaks should be avoided.

As some authors suggest, the development of a unified simulation model for the combination of ground system, heat pump, heat exchanger and building installations would be a useful task for future research. Future research should also include more detailed GSHP system designs, including storage pattern and geometry and coupling to low-temperature heating and high-temperature cooling building systems. Additionally, new designs' validation through measurements in different types of buildings would boost technological development of the concept.

5. Short Term Storage in Building Thermal Mass

Indoor air temperatures in buildings are primary influenced by external climate (outdoor temperature, solar radiation) and by varying internal loads (human activities, equipment, and lighting). This results in varying energy demands for heating and cooling on diurnal basis, with peaks occurring at different times of the day. During summer, the outdoor temperature swings and varying solar radiation during the day result in peak cooling demands around noon and early afternoon hours. During these periods of the day, the high outdoor temperatures eliminate the use of passive cooling techniques like natural ventilation. In order to maintain thermal comfort during these hours, it is necessary to remove all excess heat from the space immediately upon entry, by an energy consuming mechanical system. Similar case can be considered during wintertime, when cold ambient temperatures during late afternoon and night hours result in peak demands on the heating system of the building, a period of the day when passive heating techniques like daytime solar radiation cannot be utilized. The peak heating and cooling demands in the above considered situations will require an oversized HVAC system capable of handling the peaks of the cooling and/or heating load.

The conventional control strategies described above control the temperature in the building within a comfortable range according to the instantaneous energy demand. These control strategies ignore the thermal capacitance of the building structural mass that could be utilized to reduce the indoor air temperature variation and peak heating and cooling loads and transfer the loads to another time of the day. The storage material, referred to as thermal mass, is the construction mass of the building itself. It is typically contained in walls, partitions, ceilings and floors of the building, constructed of materials with high heat capacity (such as heavyweight concrete, bricks, tiles, etc).

According to its location in the building, there are two basic types of thermal mass, i.e. external and internal thermal mass. External mass, such as external walls and roof, is directly exposed to ambient temperature variations, while internal thermal mass, such as furniture and internal purpose-built concrete partitions, is exposed to indoor air temperature. In Figure 5-1 are shown various combinations of internal and external thermal mass utilization possibilities in a building (Li & Xu 2006). Depending on the location of the insulation layer, a concrete wall can act either as internal thermal mass (Cases B, D and F), or external thermal mass (Cases A, C and E).

In this thesis, the main interest is on internal thermal mass of buildings. The external mass is of less interest due to several reasons. First, the building envelopes of low and net-zero energy buildings have stringent requirements on insulation level regardless of the climatic location, thus changes in outdoor temperature will not have a great influence on the indoor temperature. Second, although the sun can warm an exterior surface up to 10 to 20 degrees above the outdoor ambient temperature (Clarke 2001), other factors, such as solar radiation through windows and high internal heat gains, have a much greater impact on the indoor thermal conditions.

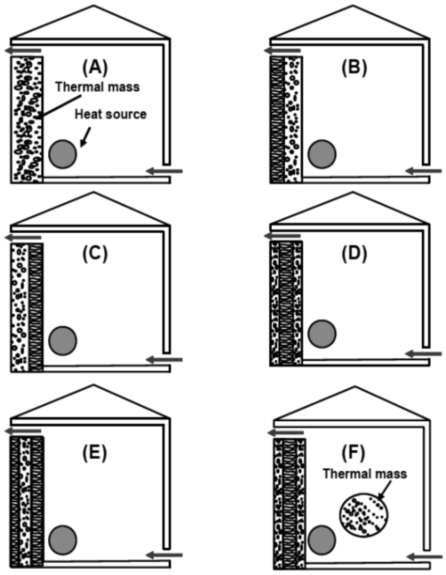


Figure 5-1: Simple building models with different location of thermal mass (Li & Xu 2006).

The thermal energy storage capabilities inherent in the mass of a building structure can be effectively used to reduce building energy consumption, reduce and delay peak heating and cooling loads, and improve comfort. Moreover, due to decreased peak energy demands, the installed capacity of HVAC equipment can be reduced, providing lower installation costs.

One of the uses of thermal mass to reduce the energy consumption for heating in buildings includes passive solar techniques (Balcomb 1983). In winter, solar and internal heat gains absorbed by the thermal mass during the day are released slowly back to the indoor air at nighttime, which can cover significant part of the heat load of the building and avoid overheating and discomfort during the high solar radiation periods at daytime. In buildings like passive houses no additional heating systems are necessary (Badescu & Sikre 2003).

During summertime, the thermal mass of the building can store large part of the indoor heat gains as well as delay the heat transfer from outside to inside, thus reducing (or shifting to a later time) the peak cooling load in the building. The time shift of the peak load and the time lag of heat release from the thermal mass to the indoor can have significant effect on the performance and operation of the HVAC system, since the time when the stored heat is released to the interior happens during evening and night hours when the indoor temperature is relatively low. In situations when the building is unoccupied during the evening and night hours, like in office buildings, it is possible to cool down the thermal mass and heat may be absorbed during the following day (Balaras 1995). In climates where the outdoor conditions are favorable (high diurnal ambient temperature variations, low outdoor air relative humidity), passive cooling techniques like natural or hybrid nighttime ventilation can be utilized to remove excess heat and cool down the thermal mass (Artmann et al. 2007, 2008). In climates with low diurnal ambient temperature variation and/or high outdoor air relative humidity, mechanical pre-cooling of the building during nighttime can be used to reduce and delay peak cooling demand (Andresen & Brandemuehl 1992; Braun 1990; Ruud et al. 1990). Shifting part or all of the cooling loads to nighttime brings the possibility to take advantage of off-peak electricity tariffs. Chiller units can be used to cool the thermal mass at night, when the cost of electricity is relatively low. The storage then can provide cooling for space conditioning throughout the day. In that way electricity costs are reduced, the efficiency of the chiller is increased and the peak electricity demand for electrical supply utilities is reduced.

During transition seasons (spring and autumn) with large ambient temperature and solar radiation variations, building thermal mass can have positive effects on indoor conditions and energy consumption for heating and cooling. It can absorb excess heat during daytime and release it during nighttime, and thereby prohibiting high interior air and wall temperature variations and sustaining steadier overall thermal environment. Additionally the thermal mass appears as important means of offsetting the mismatch between thermal energy availability and demand. Storing the excess heat during daytime reduces or eliminates the need for cooling, and releasing the stored heat during nighttime covers or reduces the heating load of the building.

5.1 Classification of Building Thermal Mass Activation Concepts and Technologies

According to the thermal storage capability of their thermal mass, there are two primary types of buildings, lightweight (butterfly-type) thermal mass and heavyweight (elephant-type) thermal mass ones (Randall et al. 1999). Lightweight buildings have highly responsive skins with large glazing areas and their indoor environmental conditions respond quickly to changes in the outdoor environment, such as solar radiation and temperature. Heavyweight buildings have much more thermal mass and lack quick response, i.e. their indoor environmental conditions react slowly to changes in the outdoor ambient conditions.

Furthermore, according to the activation principle, the thermal mass activation concepts can be divided into two main categories: Surface Thermal Mass Activation (also called passive thermal mass concepts further in the text), and Core Thermal Mass Activation (also called active thermal mass concepts or thermo-active building systems (TABS) further in the text).

The passive thermal mass concept is a traditional way to store thermal energy in materials. For example, in warm climates thermally heavy structures will create an indoor temperature which is more acceptable than the temperature in a similar building without thermal mass, due to the ability of the thermal mass to absorb the indoor heat gains (store the excess heat). The penetration depth of the stored heat depends on the thermal properties of the building fabric.

Active thermal storage is similar to the passive concept, but here the thermal energy is transferred within or between building materials by a heat carrier fluid in a duct or pipe system. In that way the heat storage and release process can be intensified and to some extend controlled.

This literature review chapter attempts to summarize the developments in short-term (diurnal) sensible thermal energy storage utilizing building thermal mass. The brief overview of concepts for thermal mass activation for enhancing the energy efficiency of buildings presented here is focusing on Passive Thermal Mass Systems and Thermo Active Building Systems (TABS). Components typically adopted, when the thermal mass activation concept is applied, include the building envelope, interior partitions, and the building structure. The overall aim is to provide the basis for development of new intelligent diurnal TES possibilities in building thermal mass, for use in combination with space heating and cooling applications.

5.2 Passive thermal mass concepts (surface thermal mass activation)

There are many techniques to passively utilize the thermal mass of a building (the thermal processes in the building thermal mass are left to follow only natural processes). These concepts include passive or active cooling by nighttime ventilation and passive solar heating systems (Lechner 2001, Badescu & Sikre 2003, Balcomb 1983). The basic principles are illustrated in Figure 5-2.

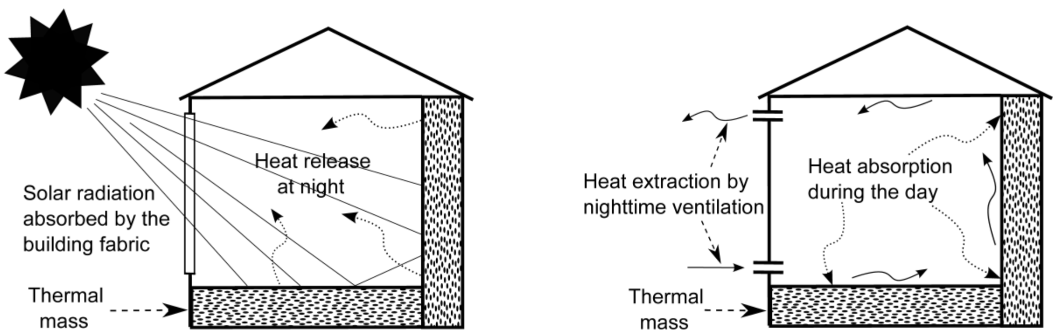


Figure 5-2: Passive solar heating (left) and cooling by nighttime ventilation (right)

Using free solar heating in buildings (Figure 5-2, left) is an example of passive thermal mass utilization. In order the concept to take place, the building has to be suitably design to accumulate the short term “free” solar heat. Large windows facing uncovered concrete floors and walls would allow storage of the penetrating solar thermal energy in the building mass. The stored heat is than released during the late afternoon, evening and night hours.

Utilizing building thermal mass by night cooling (Figure 5-2, right) can avoid or remove the need of mechanical cooling in buildings. The thermal mass of the building is absorbing the excess heat during the day, keeping the indoor temperatures within acceptable limits. Then, low-temperature ambient (or mechanically conditioned) air is circulated in the building during night to cool the thermal mass.

The thermal mass of buildings has been recognized as an important factor to consider in buildings design by many researchers. Al-Sanea & Zedan (2012) have investigated the positive aspects of high thermal mass in hot climates, while Pupeikis et al. (2010) studied thermal mass importance for the intermittent heating of buildings. Balaras (1996) and Yang & Li (2008) looked at thermal mass and cooling loads of buildings. Li et al. (2003) and Zhang et al. (2008) studied the coupling between thermal mass and ventilation, while Li & Xu (2006) discussed the general merits of thermally heavy buildings and presented a simple design method for building thermal mass determination. Interesting studies on thermal performance and energy efficiency of buildings with heavy walls were done by Bellamy & Mackenzie (2001, 2003), where the authors investigated two test houses that were identical in all aspects, except for their thermal mass.

For efficient building thermal mass utilization, thermal mass related properties like heat storage and heat transfer mechanisms; amount and distribution; and location, insulation and exposure should be considered. Additionally, site and building thermal load management dependent properties like climate; HVAC control strategies; and occupancy and internal gains have major importance.

5.2.1 Heat Transfer & Thermal Mass

For a typical internal thermal mass structure the basic heat transfer processes can be described by conduction, convection, and radiation. When the outdoor air enters the building by either mechanical or natural forces (i.e. mechanical ventilation, natural ventilation or infiltration), the thermal mass in the building absorbs or releases the heat through its surface and interior body. There is a convective heat transfer process at the surface of the thermal mass and a radiant heat transfer between them and other surfaces. The conduction heat transfer takes place in the interior body. For an effective thermal storage and release process, the surface heat transfer rate governing by the convective heat transfer coefficient and the surface area need to be sufficiently large.

Akbari et al. (1986, 1987) performed theoretical studies to determine the effect of variations in convective coefficients on the storage of thermal energy in structural materials in buildings. It was found that the thermal performance of a massive interior wall is distinct from that of a massive exterior wall. The studies concluded that variations in convection coefficients within the range commonly occurring in buildings (0.5-10 W/m^2K) can have a significant effect on the thermal performance of massive interior and exterior walls. For the considered case studies, evaluating the external walls storage capabilities, the energy consumption of well insulated buildings is less sensitive to variations in convection coefficients, compared to un-insulated ones. Additionally, the radiative heat transfer between exterior and interior walls has significant effect on the energy performance of massive buildings, and should be considered in parallel with the convective heat transfer.

It is well known that the convective heat transfer coefficient depends on the temperature difference between the thermal mass surface and the surrounding air and the air flow speed around the thermal mass. Generally in the building, it is difficult to enhance the convective heat transfer rate significantly without using a mechanical fan. Thus, the surface area of the thermal mass is a crucial design parameter.

In Hestnes (2003) was shown that the thermal mass of a building should be distributed to increase its efficiency, provided that all surfaces are in direct contact with the internal air. The mass-to-floor ratio (MFR) is a convenient parameter to evaluate the exposure of thermal mass to the indoor air. According to Diaz (1994), higher MFR improves the thermal mass performance when the internal gains are higher during the day than the night. The author has shown that large thermal mass area is more effective than thickness to improve indoor thermal conditions.

5.2.2 Buildings' Thermal Mass Properties and Thermal Energy Storage Capabilities

The location of thermal mass is an important factor for its efficient utilization for storing thermal energy. In a study of Balaras (1995) was shown that thermally heavy materials exposed directly to incident solar radiation absorb thermal energy more efficiently than materials absorbing heat indirectly by long-wave radiation and convection. Additionally, in Balcomb (1992) thermal mass location in buildings was evaluated, and results show that vertical walls are better locations for thermal mass than floors and ceilings, because the convective heat transfer coefficient for vertical surfaces are greater. Diaz (1994) evaluated the effect of thermal mass on the internal temperature of a single-zone space where location, amount and distribution of the thermal mass was explored. Results from that study show that the floor is the location where the thermal mass has the least impact on the internal temperature. The parametric evaluation concludes that the internal walls are the least effective location, but as the building structure becomes heavier, the location of the thermal mass loses its importance.

For storing heat in buildings, two important thermal properties of the materials should be considered, i.e. the heat capacity by volume and the heat-absorption rate. The first property determines the ability of the materials to store thermal energy, and the second determines the ability of the element to absorb the thermal energy.

The amount of heat required to elevate the temperature of a material by 1K, is determined by the specific heat capacity c_p, density ρ, and the volume V of the material.

For building thermal mass evaluations, it is more practical to evaluate the amount of heat per square meter, which would consider the volume of the material divided by the exposed surface area, namely the thickness of the material layer, *d=V/A*. In a multilayer wall/floor/ceiling, the total heat capacity can be calculated as the sum of heat capacities of each layer i, i.e.:

$$C_{tot} = \sum_{n} c_{p,i} \cdot \rho_i \cdot d_i \quad (J/m^2K) \qquad (5.1)$$

The total amount of thermal energy a building component can absorb according to Eq. 5.1 depends on the exposed surface area and the thickness of the material. In Balcomb (1992) is shown that during a diurnal cycle, most of the recoverable heat is contained in the first 5 cm layer and thicknesses above 10 cm provide little additional effect, assuming the properties equal to heavyweight concrete. In the international standard EN ISO 13786 (2000), the effective thermal thickness of a building component is approximated as the minimum of 1) half the total thickness of a component, 2) the thickness of the material from the surface of interest and the first insulating layer excluding coating layers, or 3) depending on the period of the variation, 2 cm, 10 cm and 20 cm for 1 hour, 1 day and 1 week respectively. The basis for this recommendation is a building component with thermal properties similar to heavyweight concrete.

Thermal diffusivity k and thermal effusivity β, Eq. 5.2 and Eq. 5.3 respectively, are useful dynamic performance indicators (Clarke 2001), when thermal mass is evaluated. The thermal diffusivity describes how fast a heat wave travels through a material. The thermal effusivity is the materials heat penetration coefficient, where materials with high effusivity will more readily absorb a surface heat flux than low-effusivity materials.

$$k = \frac{\lambda}{\rho c_p} \quad (m^2/s) \qquad (5.2)$$

$$\beta = \sqrt{\lambda \rho c_p} \quad \left(Ws^{1/2}/m^2K\right) \qquad (5.3)$$

In Table 6 are shown the thermal parameters for some common building materials. Comparing the thermal effusivities of concrete, gypsum and Rockwool from Table 5-1, show that they are in the order of 40:10:1. This means that with an increase in the temperature at the surface, concrete will absorb heat 40 times more readily than rock wool, and about 4 times more than gypsum. Thermal diffusivity and thermal effusivity can be applied to multilayered constructions by reducing the multiple layers to an equivalent homogeneous layer (Clarke 2001).

Table 5-1: Properties of building materials (Clarke 2001)

Material	Conductivity, λ (W/mK)	Density, ρ (kg/m^3)	Spec. heat capacity, c_p (j/kgK)	Thermal diffusivity, $k*10^8$ (m^2/s)	Thermal effusivity, β ($Ws^{½}/m^2K$)
Heavyweight concrete	1.30	2000	840	77	1478
Lightweight concrete	0.20	620	840	38	323
Brick	0.62	1800	840	41	968
Gypsum plaster	0.16	800	1090	19	385
Rockwool	0.033	100	710	46	48
Extruded polystyrene	0.035	25	1470	95	36

The order of materials' layers and, as already mentioned, their thermal conductivity λ, have a significant impact on the heat storage capacity in multilayered building components. If, e.g. a wall with high total heat capacity is insulated on the inside, just a limited amount of heat will be absorbed and conducted to the inner layers and the wall will behave similarly to a lightweight construction. Conversely, if the insulation layer in the same wall is on the outside, heat can be absorbed from the indoor environment, and the wall will be thermally heavy, even though the total heat capacity is the same as when the insulation layer was on the inside surface.

The optimal materials' order and thicknesses of thermal mass and insulation in building envelopes has been studied by several researchers. Shaviv (2001) investigated the influence of thermal mass and night ventilation for detached houses with four different levels of thermal mass. The study results indicate that the maximum indoor temperature is reduced with an increase of thermal mass. However, the improvement has been less significant going from a medium heavy structure to a heavy structure, than from a light to a medium heavy structure.

Similar observation was made by Norèn et al. (1999), who studied the annual energy use for heating for three different buildings with equivalent heat loss coefficients. The study concluded that a small increase in the thermal mass in a building has a lowering effect on the specific heating energy demand, but that the effect diminishes with a further increase in the thermal mass.

The effect of thermal mass and insulation location for six different wall configurations was evaluated by Kossecka and Kosny (2002) through computer simulations. The authors calculated the annual heating and cooling loads in different US climates. Results from the study showed that the material configuration of the exterior wall significantly influence the thermal performance of the whole building. The best overall energy performance was found for externally insulated configuration with internally exposed thermal mass, while the worst performance was in the case of internally insulated building envelope, which resulted in an overall annual energy demand, depending on the climate, that was 2-11 % higher than the case with externally insulated building envelope.

Slightly different approach was used by Asan (1998), where the author investigated the optimum position of thermal mass and insulation from a maximum time lag and minimum decrement factor point of view. The time lag is defined as the time it takes for a heat wave to propagate from the outer to the inner surface, and the decreased amplitude ratio of the heat wave during this process is the decrement factor, Figure 5-3. In the study of Asan, the one-dimensional transient heat equation, for different wall configurations with equivalent U-value, was solved. Two insulation boards were moved inside a massive wall, seeking for optimal performance. Based on the results, the author recommends that insulation should never be used as a whole in any location of the wall, except on the outer surface. Further, by placing half of the insulation in the center of the wall and half of the insulation at the outer surface gives high time lags and low decrement factors, and is close to the optimum value.

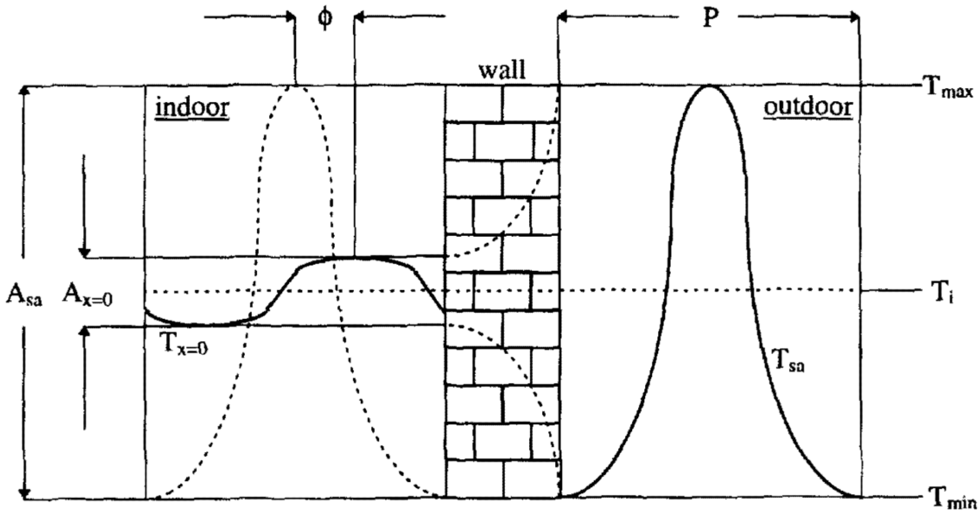


Figure 5-3: Time lag φ and decrement factor f, for a room without heat loads (Asan 2006)

In Bojic et al. (2005), the dependence of space cooling loads of residential flats on the constructions of external walls and partitions and the location of thermal insulation layer in the walls and partitions, was studied by detailed computer simulations for a typical high-rise public housing block in Hong Kong. Twelve alternative wall constructions were used in the simulations. The results indicate that insulating the envelope and the partitions could reduce the yearly space cooling load by up to 38%, but on the contrary could either increase (by up to 19%) or reduce (by up to 16%) the peak cooling demand, depending on the number and positions of insulation layers in the walls. Reduction in building's envelope and internal partitions' thermal capacity (e.g. by reducing their thickness) would lead to large increases in the peak cooling demand, by more than 60% in the extreme case.

For quantifying the thermal energy storage capability of a building there have been several approaches. The Diurnal Heat Capacity (DHC) has been developed especially for passive solar houses by Balcomb (1992). It is a measure of the capacity of a building to absorb heat from the interior space during the day, and to release the heat back to the space during the night hours. The DHC_i of a material is a function of the density ρ, specific heat c_p, conductivity λ and thickness d, and its calculation is given in Balcomb (1992). The total DHC of a building is calculated by summing the DHC_i-values of each surface exposed to the interior air:

$$DHC = \sum_{n} DHC_i A_i \quad (Wh/m^2K) \qquad (5.4)$$

It is worth noting that the DHC_i for a material increases initially with the material thickness and then decreases at around 10-20 cm, depending on the material type. This implies that there is an optimal thickness when it comes to maximum heat storage and release in a 24-hour cycle. The DHC-method can also be applied to multi-layer constructions (Balcomb, 1992).

Another measure the capability of a building to store thermal energy is the Thermal Time Constant (TTC), defined as the product of the thermal resistance and heat capacity of a unit area of a building envelope element. Its calculation is given in Givoni (1998). The TTC represents the effective thermal capacity of a building, i.e. it characterizes the effective thermal mass of the building envelope. High TTC indicates high thermal inertia and results in a stronger suppression of the interior temperature swing (Givoni 1998). The total TTC_{tot} of the building envelope equals the sum of all the TTCs of the individual surfaces divided by the total envelope area A_{tot}:

$$TTC_{tot} = \frac{\sum TTC_s}{A_{tot}} \qquad (5.5)$$

The DHC and the TTC can be used to evaluate the dynamic thermal performance of a building. The TTC is a measure on the effective heat capacity of a building when the heat flow across the opaque part of the building envelope is dominant, while the DHC indicates the thermal capacity for buildings where the internal and solar heat gains are prevailing. According to Givoni (1998b), the DHC and TTC depend on the building construction in the following way:

- External insulation with internal exposed thermal mass: Both TTC and DHC are high. Heat can be absorbed during the day and, if ventilated at night, released during the night.
- Thermal mass insulated internally: Both TTC and DHC are low. The thermal response of the building is similar to a light-weight building.
- Thermal mass insulated externally and internally: TTC is high, while the DHC is negligible, since the internal insulation isolates the thermal mass from the interior.
- Core insulation between two layers of thermal mass: TTC is a function of the internal mass and the core insulation thickness, and the DHC is a function of the internal mass.

5.2.3 Climate, buildings' occupancy and thermal load, HVAC control strategies, utilities tariff structures

Traditional ways to reduce energy consumption in buildings are to increase insulation, make buildings more airtight and reduce ventilation losses by heat recovery. Additional aspect to consider is the user behavior, which may cause substantial differences in energy use.

To move forward, towards low and near (or net) zero energy buildings, engineers and architects need to consider the use of renewable energy sources and attempt to utilize the laws of nature in the design of buildings and in the operation of installations. Building dynamics should be used in favor of assisting in indoor temperature control.

One way to do that is to use the heat capacity of massive buildings in a useful way. Typically, a heavy building can have in times higher time constant compared to a light building, so a heavy building will heat up or cool down in times slower. As a lightweight building reacts more quickly to external temperature changes, the space conditioning system must be dimensioned for a single day, the design day with the extreme outdoor temperature, while a heavy building can keep its internal temperature within acceptable limits during longer periods without heating or cooling.

In general the application of thermal mass has been found to be particularly suitable for climates with big diurnal temperature variation, to take advantage of evening heat release or night-time cooling of the building structure.

Cooling by night-time ventilation, one of the most efficient applications of thermal mass can be used if night temperatures are low enough to release heat from the building's thermal mass. In a study of Szokolay (1984), it is suggested that the appropriate diurnal outdoor temperature variation should be at least 10 K in order to get a desired cooling effect, while in Givoni (1998b) is claimed that night cooling is applicable in regions with a diurnal outdoor temperature swing of more than 15 K, and where the minimum night-time outdoor temperature in summer is below 20°C.

The influence of thermal mass and night-time ventilation in different Israeli climates was investigated by Shaviv et al. (2001). Results from the study point out that the maximum indoor temperature is linearly dependent on the outdoor temperature difference between day and night. That relation can serve as a simple tool to estimate the building thermal mass and night-time ventilation utilization potential, given the diurnal outdoor temperature swing at different locations.

Pfafferott et al. (2003) refer to a Swiss handbook on passive cooling published by EMPA, in which the limits on free cooling potential are set to 150 Wh/m^2 per day if the outdoor temperature difference between day and night is less than 5 K, and 250 Wh/m^2 per day if the difference is higher than 10 K.

For Europe, the climatic potential for passive cooling of buildings by night-time ventilation has been analyzed by Artmann et al. (2007) using a degree-hours method. All climatic zones of the continent were considered by analyzing semi-synthetic climate data produced by Meteonorm, Figure 5-4. It was shown that in Northern Europe there is very significant potential for cooling by night-time ventilation. In Central, Eastern and even in some regions of Southern Europe, the climatic cooling potential is still significant, but due to the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. If lower thermal comfort levels are not accepted during short time periods, additional cooling systems are required. The authors have pointed out that the method developed is applicable only during buildings' design phase, and is not a substitute for building energy simulations, where thermal mass, solar and internal heat gains and air-flow patterns are taken into account.

All above studies consider climate effect on thermal mass utilization for cooling load management. In a study of Mitchell & Beckman (1989) the concept of balance temperature is employed to evaluate the utilization of excess heat gains stored in building's thermal mass during daytime for reducing the night-time heating demand. The balanced temperature is defined as the ambient outdoor temperature at which the space gains and losses balance and there is no heating energy requirement. The authors claimed that, if the building thermal mass utilized for storage of heat is to have a significant effect on the energy consumption, it is important to have the balance temperature close to the average ambient outdoor temperature during the heating season. If the difference is greater than 9 K, than storage in buildings' thermal mass will have no significant effect.

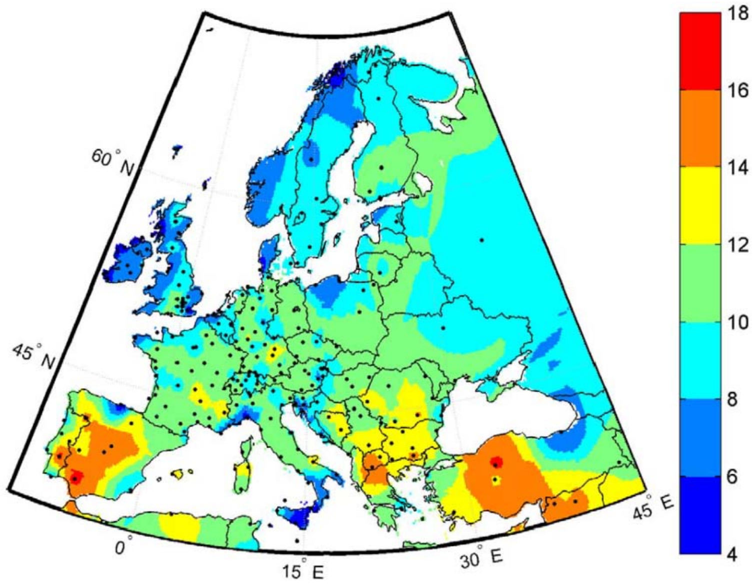


Figure 5-4: Mean differences b/n minimum and maximum temperatures (K) in July based on Meteonorm semi-synthetic climate data (Artmann et al. 2007)

There is a high potential for thermal storage in the building structure. However, control over the rate of charging and discharging of the thermal storage available using the building structure is limited by comfort considerations and coupling of the mass to the room air.

By precooling the building during unoccupied hours, the thermal storage available in the building mass can be utilized to partially shift cooling loads from daytime to nighttime. Load shifting allows reducing energy costs through: use of low cost off peak electricity rate; more favorable ambient operating conditions; reduction of peak electricity demand. Night-time ventilation and HVAC system control strategies, and occupancy periods and internal gains are of utmost importance for achieving the claimed benefits.

Office- or other buildings that are unoccupied during the night are well suited for utilizing their thermal mass. These building types have the possibility to use the night hours to cool the building structure in order to prepare the building for the next day. It is also advantageous to store excessive heat from the day to lower the heating energy needed during the night time. Buildings with 24-hour occupancy, e.g. hospitals, or buildings occupied during the night, e.g. residential buildings, have less potential for saving energy by utilizing their thermal mass (Braun 1990, Diaz 1994).

Braun (1990) conducted computer simulation studies and optimization routines, for a multi storey commercial building, in order to investigate the use of building's thermal capacity as means of reducing cooling plant operating costs. Both lightweight and heavyweight building structures, under different occupancy profiles, utility rate structures, cooling system types and weather conditions were studied. Reductions in peak electrical use of 10-35% have been achieved under proper management of building's thermal mass storage. In the presence of time-of-day rates, energy cost reductions of 10-50% were achieved. Energy cost and peak electricity demand reductions have been much less significant for 24-hour than for 12-hour occupied buildings. The most significant savings were obtained at low night ambient temperatures, when free precooling by outdoor air has been possible. The main conclusion was that the potential energy cost savings from precooling depend on the control strategies used to charge and discharge the building thermal mass.

The importance of heavyweight construction for efficient building thermal mass utilization for storage applications has been shown in a field experiment conducted by Ruud et al. (1990). Mechanical precooling during unoccupied hours was used, for an office building located in a warm and humid climate zone (Jacksonville, Florida, U.S.). Nighttime free cooling could not be employed due to high humidity. The employed precooling control was not optimized for the building under consideration, but rather the maximum possible precooling during unoccupied hours was provided. Diurnal heat capacity calculations were used to estimate the potential for thermal storage in the building. The effectiveness of building mass in storing thermal energy on a daily basis was found to be about 20%. Daytime cooling load reduction of 18% were achieved, however, due to low building thermal mass and respectively low storage capacity of the structure, there has been no reduction in the peak cooling demand.

In a computer simulation study by Andresen & Brandemuehl (1992) has been demonstrated the potential for reducing peak cooling loads and electrical demand by precooling building's thermal mass. The impact of three different precooling strategies was investigated for a single building. Results have indicated that mechanical precooling of building's thermal mass during off peak hours can reduce peak cooling loads by up to 50% compared to a strategy of turning the HVAC system off at night. Results have shown sensitivity to the convective coupling between conditioned air and building thermal mass. Thermal mass of furnishing was found to be important as well.

A major conclusion that can be drawn from the above mentioned studies is the importance of developing and utilizing building and site specific precooling control methods. In an experimental study by Morris et al. (1994), dynamic building (thermal mass utilization) control strategies were compared with night set back control at a test facility representative of a room in a large office building. Two optimal control strategies, preliminary determined through computer simulations, were considered: minimum total energy costs and minimum peak electrical demand. Experimental results have shown that up to 51% of the total cooling load could be shifted to off-peak hours and a total peak cooling load reduction of as much as 40% could be achieved. Using computer simulations, utilizing the test conditions, have shown electrical energy and demand savings of 10% and 38% respectively. Utilizing the thermal storage potential of building mass for energy savings have shown dependence on ambient conditions, utility rate structure, and coupling between the zone and the ambient through exterior walls.

Braun et al. (2001) developed a tool that allows evaluation of building's thermal mass control strategies using HVAC utility costs as baseline for comparison. Inverse models, utilizing short term measured data, were used to 'learn' system behavior and provide relatively accurate site specific performance predictions. Based on weather and solar inputs, occupancy and internal gains schedules and utility rates, intelligent thermal mass control strategies could be identified in a simulation environment using the analysis tool. Evaluation of the developed tool was performed, using measured data collected for a summer month billing period for an office building located in Chicago, Illinois, U.S., showing that the analysis tool predicted the HVAC utility costs within 5% of actual costs. Further studies were performed, using the developed tool, to examine the utility savings potential for summertime operation using various thermal mass control strategies. The 'best strategy' obtained, has shown about 40% reduction in total cooling costs as compared with night set-back control. Representative utility rates for five different climatic locations in U.S. were used (Boston, Chicago, Miami, Phoenix, and Seattle), to further examine the developed 'best strategy'. Results have shown potential energy savings in all climatic locations, except Seattle, where no time-of-use energy charges and relatively low demand rates applied.

In an overview of research related to use of building thermal mass for shifting and reducing peak cooling loads in commercial buildings, Braun (2003) found that there is a tremendous opportunity for reductions in on-peak energy and peak demand using mechanical precooling during off peak hours. The study has demonstrated that the savings potential is very dependent on utility rates, building and HVAC plant characteristics, weather conditions, occupancy schedules and control strategies. Different load control strategies using building thermal mass have been assessed, for five climatic locations in U.S., in order to identify design steps necessary to achieve widespread application of the concept.

The need for development of general guidelines and simplified analyses tools to help building designers and operators in assessing the potential of pre-cooling building thermal mass strategies on reducing energy cost for office buildings is further addressed by Morgan & Krarti (2007). The authors performed a series of parametric analysis, using the whole building simulation environment EnergyPlus, for a three-storey prototype office building replicated in four different climatic locations in U.S. The key design and operating parameters evaluated include variables like location, mass level, pre-cooling control strategies, and time-of-use utility rates with on- and off-peak periods. Results have shown that 4-8 hours pre-cooling periods were most effective in reducing peak cooling loads without increasing energy use dramatically. In terms of thermal mass level, medium and high mass levels have shown the best cost savings potential. Depending on building peak cooling demand, short peak periods offered the best potential for cost savings. Higher on-peak to off-peak energy charges and on-peak to off-peak demand charges have shown beneficial for pre-cooling of building's thermal mass for energy savings.

5.3 Active thermal mass concepts (core thermal mass activation)

Active thermal mass concepts are heating/cooling systems that are thermally coupled with a building construction having high thermal capacity (walls, floor/ceiling slab). These active building components are equipped with ducts for circulation of air or embedded pipes for circulation of heat carrier fluid (water). It is suggested to label these diverse system configurations as thermo-active building systems (TABS) according to Olesen et al. (2006), Figure 5-5. Building components with embedded water pipes are mostly used today (Meierhans 1993, Olesen 2000). Besides water-based systems, also airborne systems were developed, like TermoDeck in Sweden (Smith and Raw 1999, Karlström 2005). The ThermoDeck is an example of airborne system which can be used both for cooling and heating (Figure 5-6). Ventilation air (from main supply duct, usually located in a central corridor) is led through ducts in a concrete slab placed in the ceiling, which is used as thermal mass, and then supplied into the room.

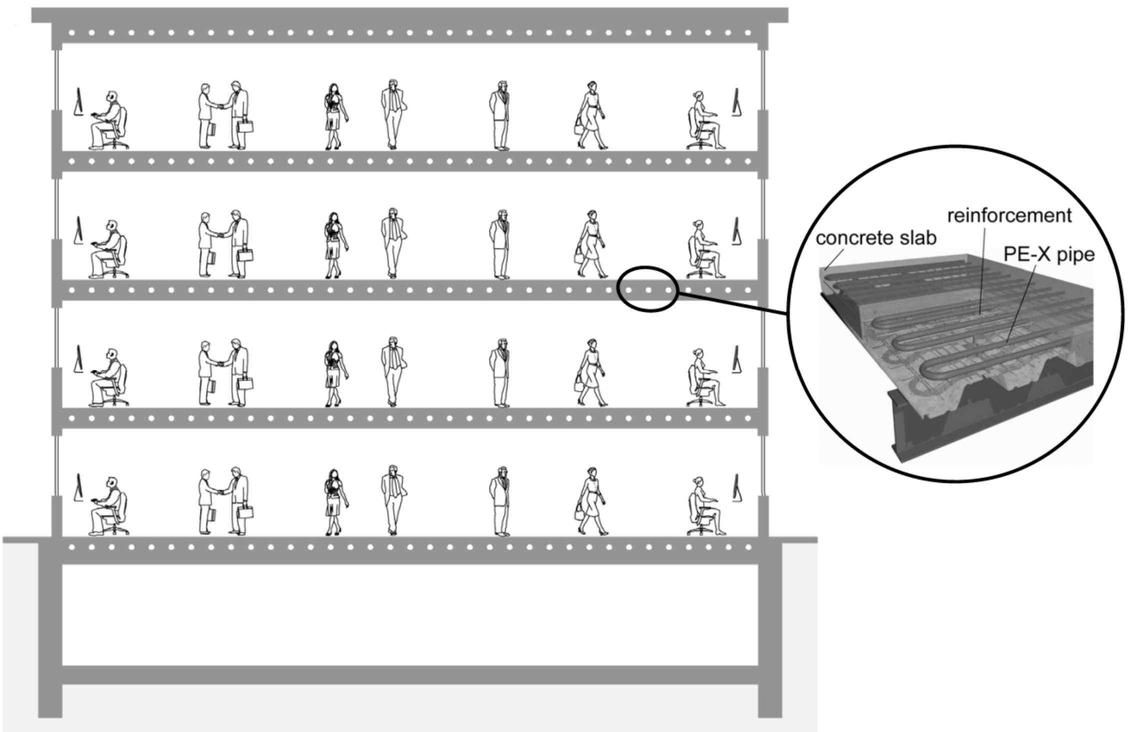


Figure 5-5: Core thermal mass activation system (Thermo-active building system - TABS)

As already mentioned, the core thermal mass activation systems can be divided according to the heat transfer media used for the activation. It can be either air (airborne systems) or water (water based systems, in which also water with an antifreeze solution can be used in certain applications). In this thesis only water-based systems are considered, since it is the mostly used concept today.

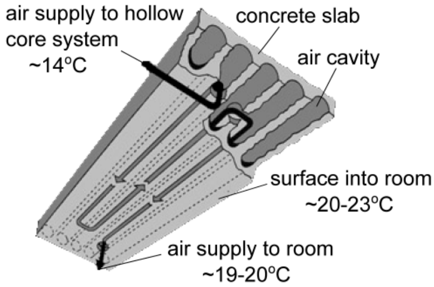


Figure 5-6: Airborne core thermal mass activation system (ThermoDeck®)

5.3.1 Thermo-Active Building Systems – Benefits and Limitations

TABS systems are mainly used in multi-storey office buildings with a low heating load in winter (10-30 W/m^2) and a moderate cooling load in summer (30-60 W/m^2). In buildings with higher energy requirements, supplementary systems should be used to address the excess demand. Influence of convection and radiation on system performance (heating and cooling capacity) can be expressed by means of combined heat transfer coefficient. The heat exchange coefficient depends, however, on the location of surface (wall, ceiling, floor) and if heating or cooling is used (Olesen 1997a, 1997b, 2000; Olesen et al. 2000).

With TABS the large thermal capacities of the building structure – such as massive floors and ceilings – is used as energy storage and is thereby integrated in the overall energy strategy of the building. By absorbing radiant and convective energy of heat gains or by release of stored energy, the slabs provide cooling or heating to the room. Through the intermediate storage of energy in the slabs, peaks in energy demand are flattened. In addition, there is no need to instantly supply the heating and cooling demand of the building to the slabs (Olesen et al. 2006), Figure 5-7. Heat and cold can be transferred with time shift and at power levels which may differ from the actual demand. In that way chillers can be operated using cheaper night time electricity.

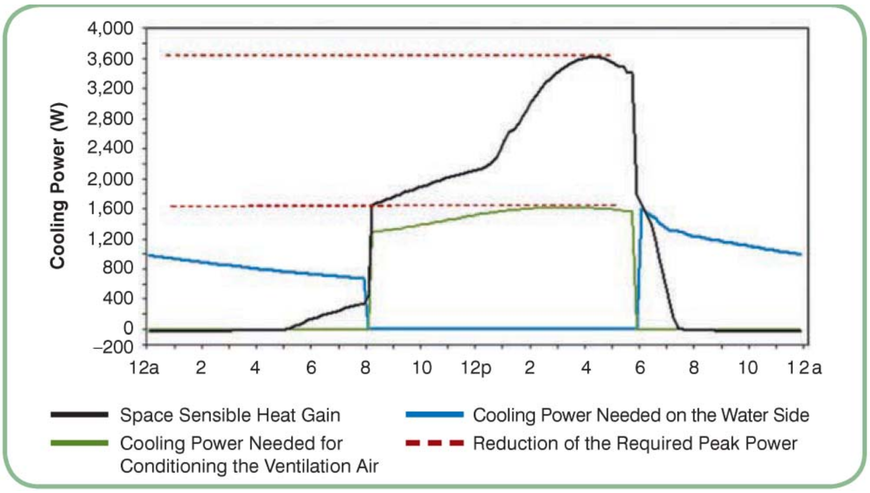


Figure 5-7: Theoretical example of peak-shaving effect (Olesen et al. 2006)

The large areas of the thermo-active surfaces allow for substantial heat flows between room and structure, even for relatively low temperature differences between the space and the heat carrier fluid. This increases the efficiency of the mechanical cooling equipment (chiller or a heat pump). It also gives the opportunity for the application of low temperature heating and high temperature cooling sources, such as geothermal energy, groundwater or outside air (Meierhans 1993, Zimmermann 1999, Koschenz et al. 1999, Lehmann et al. 2007).

In addition to their energetic performance, TABS systems have shown excellent performance in terms of room temperature control. Olesen et al. (2002) have conducted a thorough investigation of field measurements in four office buildings. A general conclusion is that the buildings can easily maintain indoor temperatures below 26°C for nearly all of the working hours and never exceed 27°C even at outdoor temperatures exceeding 30°C. Further, the amplitude of the room temperature is less than 5 K for three of the buildings and for the last the increase is less than 6 K for 95% of the time.

5.3.2 History of TABS and geographical acceptance

In the early 1990's in Switzerland, novel concepts for heating and cooling office buildings made active use of the thermal storage capacity of the concrete slabs between each story in the building (Meierhans 1993, Zimmermann et al. 1998). One of the first buildings with hydronic concrete core conditioning in Switzerland was built in 1990/1991, with a slab cooling area of 7500 m². Results in form of measurements and simulations show that the system is able to keep indoor temperatures at an acceptable level even during very hot outdoor conditions. Another building where TABS were implemented for cooling and heating purpose is the Sarinaport Office Building in Switzerland, constructed in 1994 with conditioned area of 9500 m² (Zimmermann et al. 1998).

At the beginning of 2001 in Germany, more than 60 buildings were conditioned by TABS with a thermally activated area between 250 and 40000 m² (Olesen 2001). In 2003, it was estimated that approximately one third of new commercial constructions in Germany are conditioned by TABS. In Switzerland, the installed area of TABS was estimated to be around 100000 m² (Koenigsdorff 2003). The installed area of thermo-active building systems in 2007 is estimated to amount to 490000 m² (76% office buildings and 5% residential buildings). In the U.S., TABS have not found a market yet (Roth et al. 2002) and examples of existing buildings in the U.S. served by TABS could not be found. The only available North American reference describes TABS in a Canadian university building (Tian et al. 2005).

5.3.3 Design, control, operation and integration of TABS in buildings' HVAC systems

Although there are certain similarities between TABS and the passive thermal mass utilization concepts, there is one distinctive feature of TABS, which has a major effect on system design considerations and efficient operation. The embedded water pipe circuit and additional hydronic system supplying the TABS system impose certain requirements to be considered during design and optimization of operation. Additionally, the dynamics of the system in heating and cooling mode rather differs compared to passive thermal mass systems.

Guidelines for dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems are given in the International Standard ISO 11855-4 (2012). Moreover, many researchers have investigated the design and optimal control strategies of TABS systems. Summary of some of the findings are given here.

An integral approach for the design of TABS and of their control as well as different control strategies were developed in Gwerder et al. (2008) whereas in Gwerder et al. (2009) an extension to the base control strategy for the intermittent operation of TABS applying pulse width modulation (PWM) is explained. Therefore the control aspects of TABS are quite well treated and different control solutions are available to choose from. Another aspect which has not been examined so far in the same depth is the energy efficiency of TABS. Although several studies on the energy consumption of individual buildings are available, little has been published on the implications of system design and control on the energy efficiency of TABS.

A study by Rijksen et al. (2010) presents general guidelines for the required cooling capacity of an entire office building using thermally activated building systems. On-site measurements were performed and used to analyze the predictive performance of a simulation model. In order to acquire general guidelines for the required cooling capacity of a standard office building, simulations of an entire building were used to determine the impact of variable internal heat gains and different sized windows. The required cooling capacity was compared to the cooling capacity of a system without energy buffering (e.g. chilled ceiling panels). It was found that reductions up to 50% of the cooling capacity for a chiller can be achieved using TABS.

A comprehensive analysis of primary energy consumption of TABS is given in Henze et al. (2008), by a simulation study comparing the primary energy and comfort performance of ventilation assisted thermo-active building system relative to a conventional all-air (VAV) system. The building studied was a low-energy office building for the continental climate of Omaha, Nebraska. TABS heating is accomplished using a geothermal heat pump and TABS cooling using a geothermal heat exchanger. Based on the results, ventilation assisted thermo-active cooling systems appear to be a very promising alternative to conventional all-air systems offering both significant primary energy as well as thermal comfort advantages, provided the TABS is mated with low-exergy heating and cooling sources. However in that study, no hydronic system has been considered.

Lehman et al. (2011) analyzed the impact of different aspects of TABS regarding the energetic performance of hydronic systems. Based on a simulation case study for a typical Central European office building, it is shown that the energy efficiency of TABS is significantly influenced by the hydronic circuit topology used. With separate zone return pipes energy savings of approximately 20-30% of heating as well as cooling demand, can be achieved, compared to common zone return pipes, where energy losses occur due to mixing of return water. A strong impact on energy efficiency can also be observed for the control strategy. By intermittent operation of the system using pulse width modulation control (PWM), the electricity demand for the water circulation pumps can be reduced by more than 50% compared to continuous operation. Concerning cold generation for TABS, it is shown that free cooling with a wet cooling tower exhibits 30-50% energy savings compared to mechanical chillers, if the cold source is the outside air.

In De Carli et al. (2003) the use of active thermal slabs systems is described in an innovative pilot project, the building of ZUB (The Centre for Sustainable Building) at the University of Kassel (Germany). It is an innovative demonstration building, in the frame of the IEA ECBCS Annex 37 “Low Exergy Systems for Heating and Cooling of Buildings”, designed for an annual heating demand less than 20 kWh/m^2. Data on the operation of the active thermal slab system are being collected and analyzed, in order to investigate the efficiency of different solutions and control strategies. Based on that data, in order to foresee the best working condition and control strategy, a simulation made by the commercial software TRNSYS 15 has been carried out. Finally, for a seek of completeness, a parametric study for different European climatic conditions is reported (Kassel/Germany, Venice and Palermo/Italy) to look at the possibility to use active thermal slab systems in similar buildings in different climatic conditions. The results of the simulations show that in all cases the use of thermally activated slabs allows achieving thermal comfort, but to realize also energy saving some details about external conditions have to be taken into account: prevailing heating, cooling, or both heating and cooling needs.

Another example is given in Dossi et al. (2003). In this work the design of a pilot building located in Padua (Italy) is presented. This building is equipped with a novel type of thermal active slab fed by a reversible heat pump coupled to ground heat exchanger. The design is based on the concept of night time heat-cool storage and variable comfort conditions during daytime. The design simulations for this building give evidence that TABSs allow to considerably reduce the peak loads, especially during the summer, by means of night time heat/cold storage operation. The advantage of a geothermal heat source is particularly enhanced by the peak-shaving itself, thus involving high COP's. Double price (day/night) electricity fare involves further cost saving. The simulations showed also that the control strategy (starting time of storage operation, reduced power operation, etc.) are relevant to achieve the above mentioned possible advantages.

5.4 Comparison of concepts or buildings' thermal mass activation

The different concepts of building thermal mass energy storage have different levels of development. While passive thermal mass is very well developed today some of the new design strategies were developed by combining passive and active techniques together, such as TABS. Further research should focus on optimizing costs, construction time and build ability. Also, improved control strategies should be developed and tested. Design guidelines should be developed focusing on practical applications of integrated thermal mass systems in buildings.

Cooling concepts with natural or mechanical overnight ventilation have been successfully implemented in office buildings and commercial buildings in recent years. Experience gained in low-energy office buildings cooled via overnight ventilation shows that pleasant room temperatures are achieved during summer even without air-conditioning systems. The thermal properties of the passively used thermal mass elements and surrounding environment should be considered to exert its storage ability. The surface area of the element needs to be sufficiently large to ensure sufficient heat transfer rate. Barriers for further application are related to the fact that the effect of thermal mass is dependent on the climate context. When high outdoor temperatures persist for long periods, sufficient cooling of the building's thermal mass is prevented. In such cases, mechanically supported overnight ventilation has been utilized.

Extensive research has been surveyed on passive building thermal storage utilization, e.g. the mechanical pre-cooling of building's thermal mass during night-time in order to shift and reduce peak cooling loads in commercial buildings, as well as energy consumption (Braun 2003, Pfafferott 2004, Henze et al. 2005).

Compared to passive thermal mass utilization, thermo active building systems are considerably more effective in terms of climate dependence. Due to the active utilization of the thermal mass, cooling and heating loads can be reduced and shifted to off-peak hours, which leads to lower operating costs. The temperature of the cooling/heating water can be close to desired room temperature. This means high potential for using renewable energy sources (ground source heat pumps, ground heat exchangers etc.), which can operate with high efficiency (Meierhans 1993, Zimmermann 1999, Koschenz et al. 1999, Lehmann et al. 2007). The cooling system does not have to be designed to cover the maximum heat load, and reduction of the refrigeration equipment or even its omission can be achieved. As the ventilation systems only have to be sized for the ventilation rate needed for acceptable indoor air quality, ducts can be much smaller and a suspended ceiling is not needed. The avoidance of suspended ceilings has the big advantage of reducing the total building height, resulting in significant savings on construction costs and materials used.

Barriers, however, were found for the effective and efficient utilization of thermo active building systems. TABS are suitable for buildings with low heating/cooling loads (10-50 W/m^2) (Olesen 1997a, 1997b, 2000; Olesen et al. 2000). High thermal insulation of the building envelope and proper solar shading is necessary. There should be the balance between heating losses and cooling loads, so that the system can work optimally (the same heat exchange surface is used for both cooling and heating). Without the use of suspended ceiling, the acoustical requirements must be solved in other ways.

Buildings with thermo active components cannot be expected to keep a fixed temperature. Kolarik et al. (2009) studied the occupants' responses and office work performance in environments with moderately drifting operative temperatures. Results of the experiments showed that even moderately changing operative temperature ramps were sensed by sedentary subjects when exposure times exceeded 4 h. Although, significant effects on SBS symptoms related to intensity of headache, concentration ability, and general well-being were monitored in most of the ramps, no significantly consistent effects on office work performance were found.

Further research is needed to evaluate occupant responses to the temperature drifts and the influence of these drifts on the performance of office work. Individual control of the indoor thermal parameters is possible only when the TABS are used in combination with additional air-conditioning/heating systems. Furthermore, optimization of the system control strategies, based on the experience, measurements and simulations, is needed in the first year of system operation.

6. PCM in Building Materials and Components for Enhancing Building Thermal Mass

The passive and active thermal mass activation concepts, discussed in Chapter 3, are inappropriate for lightweight buildings, such as frame buildings with no interior mass. In thermally heavy buildings, the building fabric provides the necessary thermal mass, but alternative solutions for lightweight buildings are required. Adding thermal mass to buildings as part of a retrofitting scheme is not easy because lightweight buildings often cannot support the increase in weight. Moreover, conventional TABS system can be incorporated only in new buildings; casting the embedded pipes into floor slabs as part of a retrofitting scheme is problematic.

Phase change materials (PCMs) have the potential for storing much larger amounts of thermal energy per unit mass or unit volume, compared to conventional building materials like bricks and concrete, by storing the thermal energy as latent rather than as sensible heat. Different building materials have different heat capacities. PCMs outrun substantially even materials for massive walls like concrete, brick, or sandstone, Table 6-1 (Mehling & Cabeza 2008). Exact values depend on the temperature and change dramatically within a range of only few Kelvin.

Table 6-1: Heat capacities and heat stored in a 4 K interval for different building materials (Mehling & Cabeza 2008)

Material	c_p per mass, kJ/kgK	ρ, kg/m^3	c_p per volume, MJ/m^{3}K	Q/V for $\Delta T = 4$ K, MJ/m^3
EPS	1.2	16	0.02	0.08
Mineral wool	0.8	200	0.16	0.64
Cork	1.8	150	0.27	1.08
Gypsum	0.8	800	0.64	2.56
Wood	1.5	700	1.05	4.20
Concrete	0.84	1600	1.34	5.38
Sandstone	0.7	2300	1.61	6.44
Brick	1	1800	1.80	7.20
PCM: peak values	≥ 75	800	≥ 60	
PCM: 22°C to 26°C				130

The aim of the literature review work presented in this Chapter is to evaluate the potential use of phase change materials into building materials and components for enhancing the thermal mass of lightweight buildings and improving the thermal energy load management, through passive and active building thermal mass activation concepts.

6.1 Current status and characteristics of latent heat thermal energy storage in building materials and components

The use of PCMs for temperature control is related to the potential for increasing the building heat storage capacity or thermal mass. Latent storage in phase-change materials incorporated into building materials, especially in lightweight buildings, has become a main focus of current engineering research.

There are different possibilities for incorporating PCMs into building materials. However, there are still many unanswered questions about the optimal incorporation of phase change materials in building materials and components, selecting the most suitable phase change temperature for each particular application, and integrating the storage capabilities of these materials into the overall energy and space conditioning strategies of the building.

In a work by Khudhair & Farid (2004) are summarized investigations and analysis of thermal energy storage systems incorporating PCMs for use in building applications. Development and testing of PCM wallboards and PCM concrete blocks to enhance their thermal energy storage (TES) capacity, with particular interest in peak load shifting and solar energy utilization, have been considered. The problems associated with the application of PCMs with regard to the selection of materials and the methods used to contain them are discussed.

Buddhi & Tyagi (2007) reviewed possible methods for heating and cooling in buildings utilizing PCMs for thermal energy storage. The thermal performance of various types of systems, among which PCM trombe wall, PCM wallboards, PCM building blocks, and PCM ceiling boards, were presented. All systems have shown good potential for heating and cooling in buildings through phase change materials and also been very beneficial to reduce the energy demand of the buildings.

Zhang et al. (2007) investigated published research on thermal energy storage by incorporating phase change materials in the building envelope. The basic principle, candidate PCMs and their thermo-physical properties, and incorporation methods were considered. Additionally, thermal analyses of the use of PCMs in walls, floor, ceiling among others and heat transfer enhancement are discussed. The authors showed that with suitable PCMs and a suitable incorporation method with the building materials, latent heat TES can be economically efficient for heating and cooling of buildings. However, problems related to long-term thermal behavior, durability of PCM-incorporated wallboards, fire rating and heat transfer enhancement, combination with active systems etc. still need to be focused on in future work.

In Baetens et al. (2010) is given an overview on the different kinds of PCMs suitable for building applications and their specific properties. Secondly, an outline is given on current possible building applications of PCMs such as enhanced gypsum wallboards or concrete.

Recently, a comprehensive review on the integration of PCMs in building walls has been performed by Kuznik et al. (2011). Considerations about various experimental and numerical studies regarding the PCMs integration have been discussed. All of the reviewed PCMs showed a good potential for reducing cooling loads by enhancing the storage capacity of the building envelope. This storage capacity could be enhanced with an increase of the PCM thermal conductivity. From a practical point of view, a more systematic evaluation of the various PCMs integrated in the building structure is needed, in particular in real use condition. It is pointed that, in case of numerical analysis attention must be paid to numerical modeling assumptions: convective heat transfer coefficient, use of the phase change diagram.

In Zhou et al. (2012) are summarized previous works on latent thermal energy storage in building applications, covering PCMs, the impregnation methods, current building applications and their thermal performance analyses, as well as numerical simulation of buildings with PCMs. Most of the reviewed previous researches show that the PCMs to be used in buildings should have phase change temperature between 18°C and 30°C to meet the thermal comfort criteria. In addition, properties such as chemical stability, fire characteristics and compatibility with constructional materials need to be considered. The authors have concluded that with latent heat storage with PCMs in the walls, ceilings and floors of buildings, the indoor temperature fluctuations can be reduced significantly whilst maintaining desirable thermal comfort. The concept is also useful for off-peak thermal storage, ventilation and cooling.

Soares et al. (2013) presented a review of previous research on use of PCMs in passive latent heat thermal energy storage systems, including how these construction solutions are related to building's energy performance. The review shows that passive construction solutions with PCMs provide the potential for reducing energy consumption for heating and cooling due to the peak load reduction and load shifting, and for increasing indoor thermal comfort due to the reduced indoor temperature fluctuations. The review study includes survey on research trends and discussion of some physical and theoretical considerations about the building and the potential of integrating PCMs in construction elements. Different types of PCMs and main criteria that govern their selection are reviewed, as well as the main methods to measure PCMs' thermal properties are given. Additionally different techniques to incorporate PCMs into building elements are presented. Last but not least, the numerical modeling of heat transfer with phase change, heat transfer enhancement techniques, and environmental and economic lifecycle assessments are discussed.

Summarizing the findings in the above mentioned review studies, the efficient utilization of PCMs for use in building materials and components for enhancing building's thermal mass are dependent on the following:

- Candidate PCM materials for incorporation in building materials and components, in terms of fusion temperature and latent heat of fusion, behavior during melting/solidification, fire hazards, cost and availability, and long term stability;
- Methods for incorporation in building materials and components;
- Thermo-physical properties and thermal performance.

The main characteristics are discussed below.

6.1.1 Candidate PCM materials

Selecting a suitable PCM for incorporation in building materials and components for thermal mass enhancement is a very complicated process. The potential PCMs should have a suitable melting temperature and desirable heat of fusion specified by the practical application.

Most early studies on latent heat storage in buildings focused on low cost readily available salt hydrates. Upon phase change, these materials have a tendency to supercool and they do not melt congruently so that segregation results. Phenomena such as supercooling and phase separation alter the thermal behavior of these materials and cause random variation or progressive drifting of the transition zone over repeated phase-change cycles. Although significant advances were made, further research towards the development of reliable and practical storage systems utilizing salt hydrates is needed (Paris et al. 1993, Zalba et al. 2003).

The long term stability of PCMs is required by the applications of latent heat storage in buildings, and therefore there should not be major changes in the thermal properties of PCMs after undergoing a great number of melting/solidification cycles. In an effort to avoid the problems inherent in inorganic PCMs, an interest has turned towards organic substances such as polyethylene glycol, fatty acids and their derivatives and paraffins. Those materials are more costly than common salt hydrates, and they have lower heat storage capacity per unit volume. However, some of these materials have strong advantages, such as physical and chemical stability, good thermal behavior, and adjustable transition zone (Feldman et al. 1991, Hadjieva et al. 1992, Paris et al. 1993).

In addition to thermal properties, the long term stability PCMs for incorporation in building materials and components involves additional aspects like compatibility b/n PCMs and building materials, and fire hazard characteristics and flammability of PCM-building material composite.

The main drawbacks of inorganic PCMs (salt hydrates) are their incompatibility to metals (due to corrosion, Cabeza et al. 2005) and to some extend to conventional building materials like gypsum and concrete due to their low chemical stability.

Organic PCMs' drawbacks are mainly related to flammability. In Salyer & Sircar (1990) the reaction to fire of some organic PCM materials is evaluated and possible fire-retardant additives that improve the response to fire of these materials are presented. Flammability tests on gypsum wallboard impregnated with 24% organic PCM were performed by Banu et al. (1998). The tests showed that the PCM incorporated wallboard does not meet all requirements of their building code regarding fire characteristics for building materials. The possibility of reducing the flammability of the wallboard by the incorporation of a flame retardant is discussed as well.

The long term stability, compatibility with building materials and fire hazard characteristics of PCMs are dependent to a higher or a lower extend on the incorporation method used to integrate the PCM in the building material or component. Some of these issues are discussed in the following section on "Methods for incorporation in building materials and components".

Thermal comfort is defined by the indoor operative temperature that varies depending on the time of the year. The ASHRAE 55 Standard (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and EN ISO 15251 International Standard have listed suggested temperatures in different types of buildings. Normally, the suggested room temperature is 22 - 27°C in the summer and 19 - 25°C in the winter (Category III, EN ISO 15251). In building thermal mass enhancement applications PCMs' melting temperature should be in the comfort temperature range. PCMs with a phase change temperature (18 - 30°C) are expected to meet the need of thermal comfort.

Another very important criterion for selecting PCMs is the latent heat of fusion. In order to keep the indoor temperature in the comfort range for long time (e.g. a day) without heating and cooling load, the heat of fusion of a PCM should be high enough so as to keep the wall's inner surface at the melting temperature for several hours or even a whole day.

Potential PCMs including organic PCMs, salt hydrates and eutectics are given in Khudhair & Farid (2004), Buddhi & Tyagi (2007), Zhang et al. (2007), and Zhou et al. (2012). A list of commercially available PCMs is given in Table 6-2.

Table 6-2: Commercial PCMs

PCM name	Type of material	Fusion temperature [°C]	Heat of fusion [kJ/kg]	Thermal conductivity [W/mK]	Source
RT21	Paraffin	21	160	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT22 HC	Paraffin	22	200	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT24	Paraffin	24	150	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT25	Paraffin	25	148	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT25 HC	Paraffin	25	230	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT27	Paraffin	27	179	0.2 solid / 0.2 liquid	Rubitherm GmbH
RT28 HC	Paraffin	28	245	0.2 solid / 0.2 liquid	Rubitherm GmbH
Climsel C21	Salt hydrate	21	213	0.5 solid / 0.7 liquid	Climator
Climsel C24	Salt hydrate	24	288	0.5 solid / 0.7 liquid	Climator
S27	Salt hydrate	27	190	0.48 solid / 0.79 liquid	Cristopia
STL27	Salt hydrate	27	213	- / -	Mitsubishi Chemicals

6.1.2 Methods for incorporation in building materials and components

Hawes et al. (1993) reported that the three most promising methods of incorporation of PCMs in conventional construction materials are direct incorporation, immersion and encapsulation. Additionally, novel techniques like Shape-stabilized PCMs have emerged in recent years (Inaba & Tu 1997).

The direct incorporation is the simplest method in which liquid or powdered PCMs are directly added to building materials (e.g. gypsum, concrete or plaster) during production (Feldman et al. 1991). The method is beneficial due to its simplicity and no need for extra equipment. However, leakage of the PCM when in liquid phase and incompatibility with the construction materials are the main drawbacks.

The immersion is a technology in which building components, such as gypsum board, brick or concrete are dipped into melted PCMs and then absorb PCMs into their internal pores by capillary elevation. The material is removed from the liquid PCM and allowed to cool and the PCM remains in the pores of the building material (Kaasinen 1992). The great advantage of this method is that it can be used to convert ordinary building components, e.g. wallboard, to PCM wallboard as required, since impregnation can be carried out at practically any time and place Banu et al. (1998). It has been shown that this method may have a leakage problem which is not good for long-term use Schossig et al. (2005).

Direct incorporation and immersion have different operation processes, but both methods incorporate PCMs directly in conventional construction materials. The interaction between the PCM and the carrying building material can deteriorate the mechanical properties of the building material and alter the chemical and respectively long term stability of the added PCM.

To avoid the adverse effects of PCMs on the construction material, PCMs can be encapsulated before incorporation into building materials. There are two principal means of encapsulation: macro-encapsulation and micro-encapsulation Khudhair & Farid (2004).

In the macro-encapsulation method PCMs are encapsulated in a container, e.g., tubes, spheres or panels. With macro-encapsulated PCMs, the leakage problem can be avoided and the function of the construction structure can be less affected. However, macro-encapsulation has the disadvantage of needing protection from destruction of the container and requires complicated and expensive integration into the building structure. Another problem is the decreasing heat transfer rate during the solidification process. Due to poor thermal conductivity of PCM in the solid state and the tendency of the material to solidify at the edges of the container obstruct the heat penetration towards its interior which is further increased by the small surface to volume ratio of the container (Schossig et al. 2005).

Micro-encapsulation is a technology in which PCM (paraffin) particles are enclosed in a thin, sealed and high molecular weight polymeric film compatible both with the PCM and the construction material, Figure 6-1. The microcapsules, 5-15 μm in diameter, maintain the shape and prevent the PCM leakage during the phase change process, while high surface to volume ratios are achieved resulting in high thermal conductivity during melting and solidification. Additionally, there is no need of protection against destruction of the carrying container, since the PCM is relatively even distributed throughout the building material in many μm sized capsules. It is much easier and more economic to incorporate the microencapsulated PCMs into construction materials (Schossig et al. 2005, Figure 6-2). However some studies have shown limitations on the added % of PCM in the building material, since it may affect the mechanical strength of the structure Khudhair & Farid (2004). Moreover, the application of microencapsulated paraffin in building materials needs further investigation in terms of fire hazard and fire retardation capability.

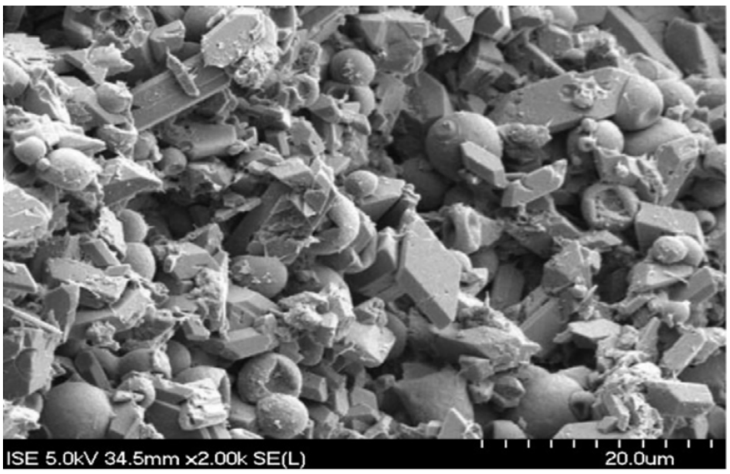


Figure 6-1: SEM image of PCM micro-capsules in gypsum plaster (Schossig et al. 2005)

Commercially available gypsum wallboard panels with microencapsulated PCM produced by BASF are provided by National Gypsum. The kind of panels is called ThermalCORE Panels, with melting point of 23°C and latent heat capacity of 70 Wh/m^2.

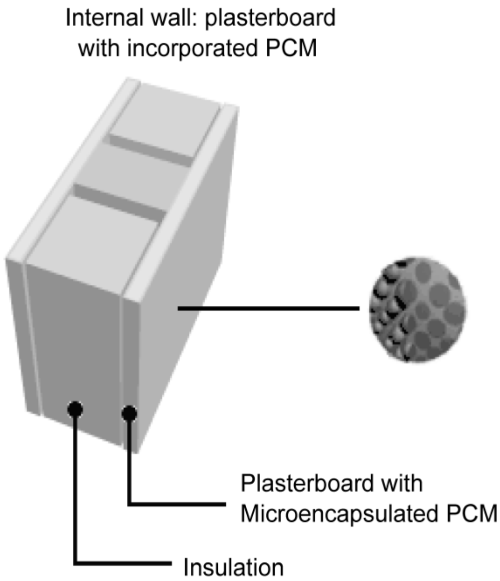


Figure 6-2: Microencapsulated Phase Change Material incorporated into plasterboard (Schossig et al. 2005)

In recent years, a kind of novel compound PCM, the so-called shape-stabilized PCM has been attracting the interest of researchers (Inaba & Tu 1997, Xiao et al. 2002). It consists of paraffin as dispersed PCM and high-density polyethylene or other material as supporting material. Since the mass percentage of paraffin can be as much as 80% or so, the total stored energy is comparable with that of pure PCMs.

6.1.3 Thermo-physical properties and thermal performance

As already mentioned, when selecting a suitable PCM for incorporation in building materials and components the phase change temperature and latent heat of fusion play major role. Melting temperature in the desired operating temperature range would provide efficient utilization of the added thermal mass, while high latent heat of fusion per unit volume would provide sufficient storage capacity in smaller amount of added PCM material.

In addition, congruent melting of the phase change material with each freezing/melting cycle, and the method of encapsulation and integration in the construction material should provide long term stability and operation of the PCM-building material composite.

Thermal analyses and thermal cycle tests on microencapsulated paraffin were performed by Hawlader et al. (2003). Results from the conducted test showed that the micro-encapsulated paraffin still kept its geometrical profile and heat capacity after 1000 cycles, Figure 6-3.

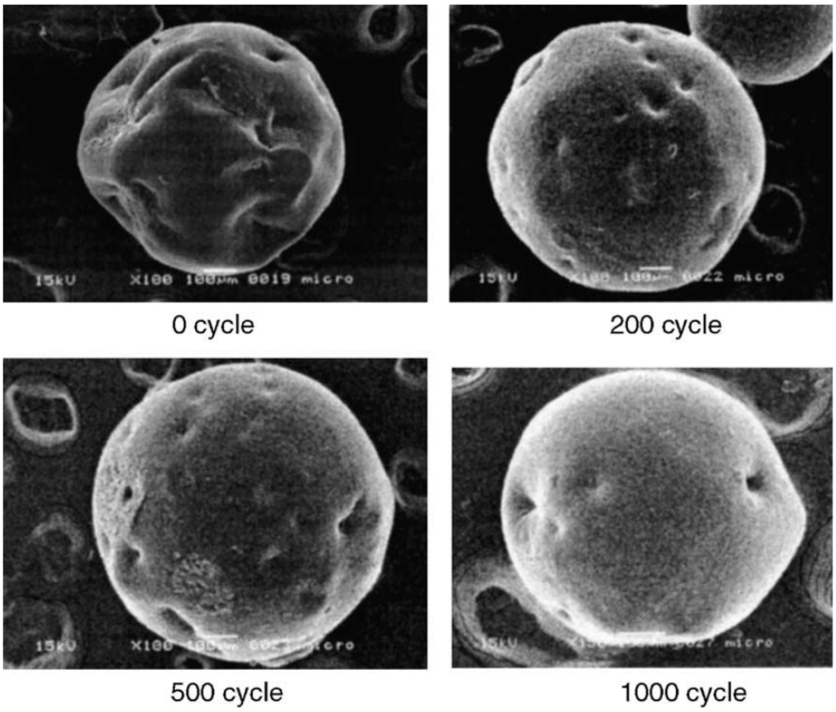


Figure 6-3: Micro-encapsulated paraffin profile evaluated by SEM at different thermal cycles (Hawlader et al. 2003)

Due to its high storage density, adding even small amount of PCM in the building structure can enhance significantly the thermal mass of the building, and may make a lightweight building behave like a massive building. However, having the necessary thermal mass in a wall does not mean that this thermal mass is used. It takes certain time to melt an amount of PCM with a given layer thickness. If too thick layers of PCM are incorporated into the building they will not melt and solidify completely by daily temperature variations, which means that part of the PCM will be rarely or never used which is not economical. To determine how much PCM can be used economically, it is necessary to determine the amount of heat that can be stored and released from a building element, at the designed/expected indoor thermal conditions. It is important to check if the heat is stored and discharged on a daily cycle. Neeper (2000) presents a detailed study on the thermal dynamics of a PCM wallboard under daily temperature variations. The results show that the daily storage capacity is limited to about 300-400 kJ/m^2.

Most PCMs suffer from the common problem of low thermal conductivities, being around 0.2 W/mK for paraffin wax and 0.5 W/mK for hydrated salts and eutectics, which prolong the charging and discharging periods. Inadequate heat transfer and overall reduction in thermal conductivities during energy recovery are identified as the main barriers affecting the performance of a PCM wallboard system.

Various techniques have been proposed to enhance the thermal conductivities of the PCMs, such as adding high-conductivity particles (Bugaje 1997), PCM incorporation in metal foams (Boomsma et al. 2003, Zhao et al. 2010) and porous graphite matrix (Py et al. 2001), inserting fibrous materials like carbon fiber brushes (Fukai et al. 2003), as well as micro-encapsulation.

Furthermore, approaches to enhance the thermal conductivity in PCM-building material composites like wallboards have been taken as well. In Velraj et al. (1999) and Stritih (2003), the use of metal fins, for heat transport enhancement, has been evaluated and has shown high potential.

Adding PCMs to building materials and components will change adversely the specific heat capacity and thermal conductivity of the resultant composite material/structure, as well as to some extend the melting and freezing temperatures of PCM-building material composite compared to pure PCM. The correct design of the building with latent heat thermal energy storage with integrated PCMs requires correct knowledge of the thermal properties of the new composite material being dependent on the % share of added PCM.

The specific heat capacity or enthalpy of a PCM-building material composite has to be known as a function of temperature. In literature are indicated the following methods to measure specific heat capacity of PCMs: differential scanning calorimetry (DSC) and T-history method.

Regarding DSC method two variants are distinguished: dynamic mode and isothermal step mode. Drawbacks and sensitivity analysis of dynamic DSC measurements are discussed and presented in Günther & Mehling (2010). The authors have pointed out that measurements with different heating rates and different sample size can give results that differ considerably from one another. The method is applicable for homogeneous samples with a very small size (1-10 mg). Conclusions from the evaluation were that the dynamic mode is not proper approach and instead an isothermal step mode or T-history mode should be used. In this work it is also stressed that DSC in general is not suitable for heterogeneous materials, like e.g. PCM incorporated in building materials.

The T-history method proposed by Zhang et al. (1999) has certain advantages compared to the DSC methods: large sample size of PCM material can be measured, the ranges of heating and cooling rates and temperatures are sufficiently large for various PCM applications, and the instrumentation and experimental set-up is simple and inexpensive.

Although well developed, the DSC with isothermal step mode and T-history methods can be employed only for testing homogeneous samples. In a recent publication Pomianowski et al. (2014) have suggested a new experimental set-up, using hot plate apparatus, and various calculation methods to determine the specific heat capacity as a function of temperature for inhomogeneous concrete with micro-encapsulated PCM. The proposed method should be compatible also for specific heat capacity determination of PCM mixtures with other building materials, e.g. plaster, in wallboards, etc.

In addition to the specific heat capacity, proper knowledge of the thermal conductivity is a key thermal parameter that has to be known to properly design latent heat storage systems or to correctly simulate dynamic models with PCMs. In literature the following methods are most often used to experimentally determine thermal conductivity of materials: hot-wire method, T-history method, hot plate measurements, hot box measurements.

The hot-wire method has been used by Frusteri et al. (2005) and Sari & Karaipekli (2007) to investigate thermal conductivity of pure PCM and PCM with different amount of graphite fibers.

The T-history method proposed by Zhang et al. (1999) can also be used to determine thermal conductivity properties of PCMs. However, the method has its limitations, e.g. it can only be applied to measure the thermal conductivity of the PCMs whose phase-change process is one clear interface between two phases.

Thermal conductivity of PCM composite materials that are always in solid state, e.g. micro-encapsulated PCM gypsum and micro-encapsulated PCM concrete materials, can be performed according to standardized steady-state procedures, e.g. with hot plate or hot box apparatus. In Pomianowski et al. (2011), is performed experimental investigation with use of guarded hot plate apparatus to determine thermal conductivity of PCM concrete composite with microencapsulated paraffin. Measurements were conducted (for temperatures below, within and above melting temperature range of used PCM) and it was concluded that thermal conductivity is almost the same regardless of if the PCM in the microcapsules is in a liquid or a solid state.

6.2 PCM in building materials and components for passive and active building thermal mass activation concepts

In this section are presented results and experiences gained form different research works on the application of PCMs in building materials and components, for building thermal mass enhancement, temperature control and peak load management. Both passive and active systems are considered.

6.2.1 Building thermal mass enhancement through PCM incorporation in building materials and components – passive systems

The passive thermal mass concepts related to the use of PCM in building materials and components benefit from the increased heat storage capacity due to the added PCM. PCM integration into gypsum, wallboards, concrete, and bricks has been studied in literature, as mentioned in the previous section of the thesis. Since the main interest in the thesis is in internal thermal mass of buildings (as mentioned in Chapter 2), only the studies and findings on PCM incorporation in gypsum/plaster/wallboards and in concrete, for increasing the building heat storage capacity or thermal mass, will be discussed here.

PCM in gypsum, plaster, and wallboards

Microencapsulated PCM incorporated into gypsum plasterboards and plasters have the potential to be used on a large scale in the construction of lightweight buildings.

Schossig et al. (2005) described the work done at Fraunhofer ISE within a German government-funded project in the period 2000-2005, extending from building simulations through small scale experiments to first measurements of full-size rooms equipped with microencapsulated-PCM plaster boards. The full scale measurements have been conducted in specially built lightweight test rooms, where one of the rooms was equipped with ordinary plaster and other with PCM plaster. The authors do not state how much of the internal surface area is covered with gypsum and where plaster boards are located. Two different PCM products were tested: dispersion based plaster with 40% mass content of PCM and 6 mm thickness and gypsum plaster with 20% mass content of PCM and 15 mm thickness. The experimental study indicated that PCM-gypsum composite helped to decrease the indoor temperature variation. Over period of 3 weeks the reference room was warmer than 28 ^{0}C for about 50h while the room with PCM-gypsum composite was only 5h above 28 ^{0}C. The authors have pointed out that use of micro-encapsulated PCM has the advantage of easy application and there is no danger of leakage compared to macro-encapsulated PCM.

The investigations of Schossig et al. (2005) have given as an outcome the development of commercial gypsum plasterboards with incorporated micro-encapsulated paraffin. Depending on temperature and local climate, the melting temperature of the microencapsulated paraffin can be chosen to be 23°C or 26°C. The first commercial products developed during that study are available on the market. The developed plasterboards have been installed in several reference buildings.

In a study by Kendrick & Walliman (2007), PCM impregnated plasterboards were evaluated for passive cooling applications in buildings, by night-time ventilation, through computer simulations using IES Virtual Environment package 'Apache'. Both, an office environment and a residential building environment were investigated. A PCM-gypsum board of 13mm thickness and 19% added PCM mass content (320 kJ/m^2 heat of fusion) was used in the office building model, and a PCM-gypsum board of 13mm thickness and 22% added PCM mass content (370 kJ/m^2 heat of fusion) was used in the residential building model. Various fusion temperatures of the PCM (21°C, 22°C and 23°C), different night-time ventilation rates and different conductivity values of the gypsum in the plasterboard (0.08, 0.19 and 0.4 W/mK) were tested.

Results for the office building model have shown that the most significant improvements are achieved at fusion temperature of 22°C giving the best overall cooling performance. In all simulation case studies it has been shown that PCM-gypsum boards cannot provide the required thermal comfort, and supplementary mechanical cooling would be necessary. For the case with PCM with 22°C, mechanical cooling with a set point of 24°C has been used, where the effect of added by the PCM thermal mass has resulted in 50% reduction in the peak cooling load and 20% reduction in the cumulative cooling load, compared to the reference case with conventional gypsum boards. In addition, increasing the thermal conductivity values of the gypsum in the plasterboard, have resulted in increased performance in terms of room temperature control and better utilization of the added PCM material.

The general conclusion of Kendrick & Walliman (2007) is that use of PCM-gypsum boards has significant advantages for both commercial and residential building applications, provided that sufficient night-time ventilation is allowed.

In Voelker et al. (2008) was developed gypsum board with incorporated micro-encapsulated PCM with melting temperature range between 25 ^{0}C and 28 ^{0}C. The developed PCM-gypsum boards were tested in two identical lightweight test chambers. In the first one, the walls were covered with the PCM plaster boards, and in the second one, with ordinary plaster boards. The thickness of the gypsum board was varied between 1cm and 3 cm, but the authors have not stated the PCM-gypsum ratio in the developed gypsum boards.

Test series were carried out under controlled conditions and it was discovered that during warm days in the room with PCM plaster boards a reduction of the peak temperature of about 3 K in comparison to the room without PCM can be achieved. The temperature in the test chambers was allowed to fluctuate from 14 ^{0}C to 35 ^{0}C. In real building condition that high temperature amplitude would not be acceptable and respectively the utilization of the latent heat of PCM in the gypsum boards would be decreased.

In Kuznik & Virgone (2009) was tested a composite micro-encapsulated PCM and copolymer product that contained 60% of microencapsulated paraffin (ENERGAIN® from Dupont de Nemours Society). The thermal conductivity of the product, determined guarded hot-plate apparatus, was 0.22 W/mK in liquid and 0.18 W/mK at solid state. Melting and solidification points of the material, determined through DSC method, were 13.6 ˚C and 23.5 ˚C respectively.

The thermal performance of the PCM-copolymer composite wallboard was tested experimentally in specially designed full scale test room. The test cell ambient environment was totally controlled so that a typical day can be represented (in terms of temperature and solar radiative heat flux). Effect of the PCM was investigated for a summer day, a winter day and a mid-season day, in a comparative manner for test room with PCM and without PCM composite boards on the walls.

The obtained results show that for all test cases the PCM wallboards allow reduction in the indoor air temperature compared to conventional wallboards. The indoor air temperature decrement factor has been between 0.73 and 0.78 and the air temperature has been lowered with up to 4.2K in the room with PCM wallboards. Additionally, due to the lower wall surface temperatures in the cases with PCM wallboards, the natural convection in the room has been enhanced and there has been no thermal stratification compared to the room with conventional wallboards.

As observed also in some of the previous studies mentioned here, the allowed indoor temperature fluctuation for all test cases has been very high. For example, for the summer day test cases, the indoor air temperature was allowed to fluctuate between 19 ˚C and 32 ˚C for the room without PCM and between 19 ˚C and 29 ˚C for the room with PCM. By using additional equipment in the test room to reduce the indoor temperature fluctuations, e.g. example solar shading, the utilization of PCM in the room with PCM wallboard would be smaller and the improvement compared to the room without PCM would be reduced.

In Oliver (2012), the performance of a gypsum board including 45% by weigh of micro-encapsulated PCM (paraffin) and some additives, has been studied experimentally. The micro-encapsulated PCM material use has been Micronal DS5001X by BASF, with 26 ˚C melting temperature and 110 kJ/kg latent heat of fusion. An experimental test facility has been designed and built to simulate the hygrothermal conditions of any room or building. It consists of an insulated closed air circuit adiabatic box, in which air is put in motion by a controlled fan. The air temperature can be risen up through a heater to reach selected conditions.

The influence of different parameters and variables that have significant influence on heat storage in buildings (e.g. air temperature and air velocity, material position) has been studied. The thermal storage capacity of boards with PCMs has been evaluated and compared for different board thickness, % of added PCM, and board location (cladding or free standing).

Experimental results indicated that the melting rate of PCM depends on the air velocity and temperature of the room, especially in the areas close to the material (e.g. walls and ceiling). Increased air velocity improves the storage capacity utilization. The low thermal conductivity of PCM-gypsum composite influences the rate of phase change and causes certain time lag b/n room temp and PCM-gypsum board temperature. The author has concluded that the thermal storage capacity utilization of boards in free position is improved up to 33% compared to when they are used as cladding elements, due to the fact that in free position the board is in contact with surrounding air and exchanges energy on both sides.

In a seek of completeness, the PCM-gypsum board thermal performance is compared to other building materials and components under the same boundary conditions. Results have shown that the gypsum board with 45% PCM mass content stores 5 times more energy per unit mass than a brick wall with PCM, 9.5 times more energy than a brick wall, and almost 3 times more energy per unit mass than a common gypsum board.

In the work of Oliver (2012), the indoor temperature, to which the PCM-gypsum board was exposed and greatest benefits achieved, has been too high to represent acceptable indoor temperatures (tests performed at 25°C, 30°C, 35°C or 40°C, and significant benefits achieved for temperatures of 30°C and above). Decreasing the indoor temperature would decrease the performance of the PCM-gypsum panels. Additionally, the indoor temperature has been kept constant during the experiments, which does not represent the real conditions in buildings with thermal mass utilization, where the indoor temperature is drifting during the day from morning low to afternoon peak values.

PCM in concrete

During the last years, several studies on incorporation of PCM in concrete have been documented. In Cabeza et al. (2007), experimental set-up consisting of two identical cubicles made of concrete, where one is built of conventional concrete and one of new concrete with incorporated 5 % by weight micro-encapsulated PCM, was built. The cubicles were used to evaluate the temperature variation and the effect of added PCM in decreasing the indoor temperature fluctuations. The obtained results revealed a decrease in the temperature fluctuation in the room with PCM-concrete composite and a 2h shift of the temperature peak in the wall.

Full scale experimental investigation of the use of PCM in concrete floors has being carried out by Entrop et al. (2011). Four identical chambers of the same size were constructed, two with PCM concrete floors and two with ordinary concrete floors. The only heat source used in the chamber has been the solar irradiation through the windows, and the PCM in the floor has been well exposed to direct solar radiation with no any floor covering used. Results from the study indicate that this technology could decrease the temperature fluctuations in the experimental chambers. However, in practice, it would be unusual to use concrete floor without any kind of covering, such as wood or tiles, that would to a higher or a lesser extend alter the thermal activation of the PCM material in the concrete floor. Therefore, it would be difficult to implement the concept on a broader scale in practice.

In the studies of Cabeza et al. (2007) and Entrop et al. (2011) have been shown certain potential benefits of PCM incorporated concrete applications for thermal mass enhancement. A major drawback in both studies towards practical applications is that in both cases the diurnal indoor temperature has fluctuated from very low to very high values, which due to thermal comfort requirements among others, would not be acceptable by any means in a real building. Therefore, the energy accumulation would be lower in practice compared to the presented experimental set-ups.

6.2.2 Building thermal mass enhancement through PCM incorporation in building materials and components – active systems

In addition to the passive thermal mass concepts discussed in the previous section, there has been increased interest in PCM integration into floor and ceiling radiant heating and cooling systems for increasing the building heat storage capacity or thermal mass. In these applications, heat or cold is stored in the PCM during off-peak electricity hours, and the stored thermal energy is released to the space during peak energy demand hours. The different concepts considered in the present section can be attributed to thermo-active building thermal mass utilization strategies for room temperature control and storage of thermal energy for heating and cooling purposes.

PCM in radiant floor heating and cooling systems

Farid & Kong (2001) investigated, through experiments and computer simulations, the possibility of incorporating PCM in the concrete slab of a floor heating system. The idea was to use the increased thermal mass for heat storage for shifting some of the heating demand from peak to off peak electricity periods. Two concrete slabs with embedded water pipes were used in laboratory tests to simulate the floor heating system. Spherical plastic nodules (75 mm diameter), containing $CaCl2 \cdot 6H2O$ (calcium chloride hexahydrate) that melts/solidifies at 28°C with a latent heat of fusion of 98 kJ/kg, were incorporated in one of the slabs (PCM content of 12%). The slabs were heated up for 8 hours (off peak electricity night-time period) and allowed to discharge the stored thermal energy during the following 16 hours (peak daytime electricity). The experimental results for the PCM-concrete slab showed much lower surface temperature fluctuations (25-31.5°C) compared with the plain concrete slab (22.5-36.5°C), and sufficient heat storage capacity to maintain an acceptable surface temperature, targeted to about 24°C, during the whole 24 hours period. A one-dimensional computer simulation model, based on the effective heat capacity method to encounter the phase change, of the floor heating system was developed to be used for optimization and design. Reasonable agreement between the measured and numerically predicted performance was obtained. The authors have pointed out the importance of the quantity and melting/solidifying temperature of the PCM used in order to achieve sufficient heat storage and release and desired surface temperature variation.

In Lin et al. (2005), under-floor electric heating system with shape-stabilized PCM plates was investigated through an experimental study in a prototype test room. Shape-stabilized PCM plates developed by the authors (75% dispersed paraffin, with phase transition temperature of 52°C and 200 kJ/kg latent heat of fusion, and 25% polyethylene as supporting material) were integrated in the floor heating system, between the electrical heating element and the wooden cover. The thermal mass integrated in the floor heating system was used for off-peak storage of thermal energy (night-time charging and daytime discharge of the stored heat). The aim of the experimental study was to determine the thermo-physical properties of the shape-stabilized PCM and evaluate the thermal performance and feasibility of the proposed heating mode. The results have shown that the upper surface temperature of the PCM plates can be kept near the phase transition temperature and about 54% of the electricity used for heating could be shift from peak to off-peak period.

The experimental data from Lin et al. (2005) was used to verify a computer simulation model, developed by the same authors (Lin et al. 2004) and based on the enthalpy method to encounter for the phase change, of a room applying the floor heating system with shape-stabilized PCM. Good agreement between measured and simulated data was obtained. The developed simulation model was further used to investigate the use of the proposed under-floor heating system in various building types and climate conditions, and to evaluate the influence of different parameters on system performance. Among the factors of main importance, the authors identified that the PCM melting/solidifying temperature is of primary importance for determining the characteristics of the heat source, the amount of PCM and the latent heat of fusion were directly related to the thermal energy storage capacity of the system, and the thermal resistance of the floor is mainly dependent on the air gap thickness between the wooden floor and the PCM plates. A proper control method should be used to keep the indoor temperatures within comfortable range and operate the system efficiently in energy terms. Dividing the floor into separate zones and control based on previous day mean indoor temperature was elaborated to show the feasibility of the under-floor heating system with shape-stabilized PCM. The results have shown that, if properly designed, the system can be used in various climates, and that the developed computer simulation model can be used to design such kind of under-floor electric heating systems.

In the paper of Jin & Zhang (2011), a double layer PCM floor was evaluated, though computer simulations based on the effective heat capacity method to encounter the phase change, for combined heating and cooling load shifting from peak to off-peak periods. The floor consists of wooden surface layer, PCM layer for cooling, PCM layer for heating, concrete layer with embedded water pipes and insulation. The embedded water pipes system is operating during off-peak hours (23:00-8:00) and not operating during peak hours (8:00-23:00). The boundary conditions for water and space air temperatures have been 52°C and 19°C for the heating case and 7°C and 26°C for the cooling case. The authors investigated the effect of melting temperatures, latent heat of fusion, and location of PCM layers for heating and cooling on the floor surface heat flux and temperature. Optimum phase change temperatures were found to be 18°C for cooling and 38°C for heating. Exchanging the location of the PCM layers for heating and cooling has changed the optimal melting/solidifying temperatures to 33°C and 16°C respectively. Minor effect on system performance was reported, depending on PCM layers location, if optimum melting/solidifying temperatures for the two PCM layers are selected. Compared to a floor system without PCM, the system with PCM provided less fluctuation in the floor surface heat flux and temperature, and an increase of 41.1% and 37.9% of the peak heating and cooling energy release when the heat of fusion of PCM is 150 kJ/kg. Increasing the thickness of the PCM layers or their latent heat of fusion has resulted in more stable surface heat flux and temperature variation.

PCM in radiant ceiling heating and cooling systems

In Koschenz et al. (2004), the development of a thermally activated ceiling panel for incorporation into lightweight and retrofitted buildings is described. The active control of the thermal storage has been achieved by means of an integrated capillary tubes system, operated during off-peak night-time hours. A numerical model, for computation of the thermal behaviour of the ceiling system with incorporated PCM has been developed. Calculations have been performed to determine the necessary thermal properties of the ceiling panel, designed for cooling a 24 m^2 experimental office room. The design thermal conditions in the range of 21-28°C have resulted in desired surface temperatures of the ceiling panels in the range 21-24°C, which determines the melting/solidifying range for the microencapsulated PCM. The estimated cooling load for standard office conditions has been 320 Wh/m^2 per day and average cooling load of 40 W/m^2 for 8 hours of occupancy. With the prerequisite to achieve thermal storage capacity equal to the daily cooling demand of the space, in order to allow for a night-time operation of the active embedded water pipes system, a 5 cm gypsum ceiling panel, with incorporated 25% (weight fraction) microencapsulated paraffin with latent heat of fusion of 110 kJ/kg, was designed. The needed storage capacity was achieved by a total amount of 13.3 kg/m^2 of PCM.

Moreover, laboratory hot box tests have been performed to verify the system's performance. Fairly good agreement between numerical and experimental conditions has been obtained. Measurements showed that the stored thermal energy has been 290

Wh/m^2 per day, which is about 10% lower compared to simulation results. The authors have attributed the lower storage capacity to the slightly lower amount of microencapsulated PCM incorporated in the gypsum achieved in practice, compared to assumptions made for the computer simulation model.

Kalz et al. (2007) performed a computer simulation study on the performance of thermally activated building systems with phase change materials for a lightweight building. Grid conditioning system (ceiling suspended capillary pipes embedded in a 15 cm plaster; water flow rate 6 l/m^{2}h, night-time operation 10 p.m. to 6 a.m.) was compared to a grid conditioning system with PCM (20% microencapsulated paraffin incorporated in the plaster; water flow rate 6 l/m^{2}h, operation 10 p.m. to 6 a.m.), and to a passive suspended ceiling system with PCM (15 cm plaster panels with 20% microencapsulated paraffin). Additionally, the operation of the three systems was compared to cooling by 4h^{-1} night-time ventilation from 10 p.m. to 6 a.m.

The different cooling strategies were evaluated for a 20 m^2 office room. For the systems with PCM, six different melting ranges of the material were examined in the study (18-21°C, 19-22°, 20-23°C, 21-24°C, 22-25°C, and 23-26°C). A total amount of 2 kg/m^2 of PCM have been used, and the latent heat of fusion of the plaster-PCM mixture has been 18 kJ/kg.

Results from the study show that compared to a free running building, the night-time ventilative cooling strategy has resulted in 5.4 K decrease in the mean operative temperature. Night-time ventilative cooling combined with passive suspended ceiling panels with PCM have reduced the maximum average room temperature with 1.3 K compared to night ventilation only. Grid conditioning only, has resulted in 0.5 K reduced average operative room temperature, compared to night-time ventilation with PCM suspended ceiling. While the relatively high ambient air temperatures considerably limit the modulating effect on temperature fluctuations through PCMs, an active discharge of the PCM storage through capillary tubes taps their full potential. When the PCM storage is actively discharged, a reduction in the average operative room temperature of 1.8 K and 1.2 K compared to the strategies with night-time ventilation with PCM suspended ceiling and the grid conditioning, respectively, has resulted. A melting range of 19-22°C was found to be most favourable according to the average and the peak operative room temperatures.

In the work of Pomianowski et al. (2012), the incorporation of PCM in conventional TABS system (prefabricated concrete hollow core deck with embedded water pipes) for heat storage and cooling is investigated through computer simulations using COMSOL and BSim. The optimal location and amount of the PCM has been evaluated in terms of increased storage capacity and storage utilization. A mixture of concrete and micro-encapsulated PCM in different ratios has been used as the PCM composite, and different PCM layer thickness and location in the concrete slab, and heat transfer coefficient (convective + radiative) between slab surface and room space are investigated. Four TABS system activation modes were considered: passive mode where the embedded pipes system is not operational, 24 hours continuous operation, 12 hours night-time operation, and 8 hours night-time operation.

Results from the passive mode of operation have shown that the heat transfer coefficient at the slab surface has a dominant role in activating its thermal mass, and the PCM layer should be located at the slab surface facing the conditioned space. For small amounts of added PCM and high heat transfer coefficients no improvement in the heat storage capacity has been observed. The results suggest an optimal PCM layer thickness of about 3 cm in the present study. Further increase of the amount of PCM incorporated in the slab has proven disadvantageous in terms of utilization of the added thermal mass. The low thermal conductivity of the PCM material has decreased the heat penetration in the slab and prevented the full activation of its thermal mass.

With regards to the activated TABS system, it has been observed that the added PCM layer have had some damping effect on the cooling performance of the thermally activated deck. The authors have pointed that the cooling effect of the TABS system has been much higher than the increased heat capacity that could be used to store heat in the slab.

The general conclusion of Pomianowski et al. (2012) has been that due to decreased thermal conductivity and density, by the added micro-encapsulated PCM, and the insignificant increase of specific heat capacity in PCM-concrete composite, compared to concrete alone, the potential for improvement with regards to added PCM is insignificant.

In Tzivanidis et al. (2012), parametric analysis of a radiant cooling ceiling system with PCM-embedded piping are performed, based on a transient three dimensional finite difference computational model. Cooling pipes were embedded in a PCM layer located between the lower surface of the concrete slab and the indoor finishing layer of the ceiling. The effective heat capacity method, utilizing experimental data, was used to encounter the phase change. The systems was aimed at increasing the ceiling thermal mass for smoothing daily peak cooling loads and provide operation under reduced night-time electricity price. The authors have defined the following main parameters influencing the system performance in terms of delivered cooling power and achieved indoor air temperatures: embedded pipes spacing and location depth within the PCM layer, cooling water temperature, cooling duration, the amount of PCM (layer thickness), PCM thermal conductivity and phase change temperature range. The values of these optimum system parameters are dependent on the magnitude and daily variation of the space thermal loads.

Results from the study suggest that the melting/solidifying temperature range of the phase change material should be selected within the thermal comfort indoor temperature range. The latent heat of fusion and amount of PCM determines the storage capacity, while the thermal conductivity of the material has shown crucial to the efficient utilization of that storage capacity. The pipes should be located in the center of the PCM layer, and pipe spacing is related to PCM layer thermal conductivity and should ensure efficient discharging of the stored thermal energy. Cooling water temperature and cooling duration have to be determined with care since these parameters ensure the unloading of the stored thermal energy and are directly related to the primary energy used by the cooling system. Sufficient temperature difference between cooling water temperature and PCM solidification temperature should be ensured, however too low water temperatures may result in excessive energy consumption.

Compared to a system with pipes embedded in the concrete, the PCM based system has achieved lower mean indoor temperatures and lower amplitude of the daily temperature fluctuations for all parameters values. The authors conclude that proper combination of the main system parameters would result in close to optimum system performance in which full advantage of the PCM storage capacity is taken. This would correspond to fully melted and solidified PCM material at the beginning and end of the night cooling cycle, under minimum night cooling duration and maximum cooling water temperature, and providing the required indoor thermal conditions.

Experiences and design considerations for PCM in thermo-active building construction

The results presented in different studies show the enormous potential of integrating phase change materials in thermally activated construction for increasing building's thermal mass. The added thermal mass allows decoupling of the heating and cooling demand of the building from the heat and cold production. Peak heating and cooling loads during daytime can be covered by the thermal energy stored in the PCM, and the heating and cooling production can be shifted to night-time period when of off-peak electricity and/or natural cold sources (cold night air) can be utilized to achieve energy and cost savings (Farid & Kong 2001, Lin et al. 2005, Koschenz et al. 2004, Tzivanidis et al. 2012). However, the efficient integration and operation of these systems depend on a number of key parameters.

PCM integrated in the building's floors, walls and ceilings can be considered as distributed energy storage system, where no extra space for the storage is needed. The large surface areas used (like in conventional radiant heating and cooling systems) allows for small temperature difference between surface and room ambient. That would result in selection of PCM melting/solidification temperature range close to the conditioned space ambient temperatures, and respectively in the utilization of low-temperature for heating and high temperature for cooling (Koschenz et al. 2004, Tzivanidis et al. 2012).

The small temperature difference between conditioning space surfaces and the ambient will result in small enough energy fluxes, which can be achieved by a heat storage/release from the PCM material. As suggested in most of the studies, the PCM should be integrated as close as possible to the surface of the floor/ceiling in order to ensure efficient heat exchange with the indoor space. High heat transfer coefficient (convective + radiative) between conditioning surface and room space should be aimed for efficient heat exchange between the storage and the space (Pomianowski et al. 2012). While in ceiling embedded systems the PCM material can be in close contact with the ambient, in the case of floor heating/cooling system the thermal resistance between PCM and ambient (due to surface finishing layers - wood, tiles, carpets, etc.) will have significant impact on system performance (Lin et al. 2004, Jin & Zhang 2011). Additionally, since the thermal conductivity of the PCM has significant effect on the heat transfer through the material and respectively its ability to absorb and release thermal energy, high thermal conductivity in the PCM layer should be aimed.

As already mentioned the purpose of adding PCM in active building constructions is to increase building storage capacity to accommodate the daily heating and cooling needs. Due to its high storage density, adding even small amount of PCM in the building structure can enhance significantly the thermal mass. However, having the necessary thermal mass (amount of PCM) in the floor/ceiling heating/cooling system, to accommodate and shift to night-time the daily heating and cooling loads, does not mean that this thermal mass is used efficiently. In order to ensure the complete utilization of the added thermal mass, the PCM material should melt and solidify completely during the 24 hours cycle. It takes certain time to melt an amount of PCM. If too thick layers of PCM are incorporated into the building they will not melt and solidify completely by daily temperature variations, which means that part of the PCM will be rarely or never used which is not economical. To determine how much PCM can be used economically, it is necessary to determine the amount of heat that can be stored and released from a building element, at the designed/expected indoor thermal conditions. The main system parameters to consider are PCM melting/solidification temperature range, the latent heat of fusion and thermal conductivity of the material, heat transfer coefficient (convective + radiative) between conditioning surface and room space, and the radiant floor/ceiling system construction (Pomianowski et al. 2011, Koschenz et al. 2004, Tzivanidis et al. 2012).

System performance, in terms of thermal comfort, gives certain advantages compared to a conventional TABS system. Due to the latent heat storage principle in the system with PCM, there is much lower surface temperature fluctuation expected compared to plain concrete slab systems, which would result in lower temperature asymmetry in the space. However, again care should be taken about the installed amount of PCM. For example, in a radiant ceiling cooling system, if the amount of installed PCM is insufficient to accommodate the daily cooling loads will cause the PCM to melt completely, and due to the lack of further cooling capacity the indoor temperatures will increase rapidly (Koschenz et al. 2004).

6.3 Summary on thermal mass enhancement through PCM incorporation in building materials and components – towards research goals of Chapter 5 and Chapter 6

PCMs absorb thermal energy when they change phase from solid to liquid (melting), and release the stored heat when the material changes phase from liquid to solid (solidification). The phase change typically occurs over a small temperature range around their melting point (fusion temperature) and as a result the material exhibits very little temperature change over this range.

Paraffin waxes, due to their availability and easily adjustable phase change temperature, are seen as promising materials for use in building materials and components (Khudhair & Farid 2004, Tyagi & Buddhi 2007, Zhang et al. 2007). With the development of PCM microencapsulation (Jahns 1999), a significant breakthrough has been achieved in the incorporation of PCMs into building components such as gypsum boards, plasterboards, floor tiles, bricks, concrete, etc. (Tyagi et al. 2011). However, cost issues related to the microencapsulation process represent a substantial barrier for the widespread adoption of these applications.

Plasterboard is the most widely used wall and ceiling lining material in lightweight buildings. Use of PCM-plasterboards instead of conventional plasterboards has the potential for increasing the thermal mass of lightweight buildings and can help to avoid overheating problems in such buildings. Phase change materials with fusion temperature close to the desired mean room temperature would provide effective thermal storage capacity, while the large surface area would enhance the heat transfer and respectively the efficient utilization of that distributed thermal mass.

Plasterboards with incorporated microencapsulated PCM, for thermal mass enhancement and room temperature control, have been studied experimentally and in numerical simulations (Schossig et al. 2005, Voelker et al. 2007). The published results have shown their potential for decreasing indoor temperature variations, in comparison with conventional plasterboards. PCM melting temperature, amount of PCM used, and the permitted indoor temperature variation have been identified as the most important parameters influencing the efficient utilization of added thermal mass. The importance of night-time ventilation rates and supply temperatures for cooling efficiency has been emphasized for these passive thermal mass utilization principles (Schossig et al. 2005, Walliman et al. 2009).

In the past few years more experimental studies on PCM plasterboards have been documented (Kuznik et al. 2009, Oliver 2012). In these studies it has been shown that gypsum can be combined with up to 45% by weight of PCM when the board structure is reinforced with some additives and with up to 60% by weight in wallboard composites.

In addition to the passive thermal mass concepts there has been increased interest in ceiling mounted radiant cooling panels, where the PCM provides the necessary thermal mass and an embedded pipe system provides active discharging of the stored thermal energy (Koschenz et al. 2004, Kalz et al. 2007). In these applications, excess heat is stored in the PCM plasterboard during peak energy demand hours, and the stored thermal energy is later extracted from the building during off-peak electricity periods. This approach is known as a thermally activated building thermal mass utilization strategy for room temperature control and storage of thermal energy for cooling purposes.

As in the passive applications of PCMs, their melting temperature and the amount of PCM used would determine the indoor thermal conditions and the ability of the system to shift the cooling load. The active discharge strategy for the PCM storage through the embedded pipes system taps the full potential of the added thermal mass, making it independent of the outdoor climate conditions.

PCM-plasterboard panels for suspended ceiling installations are considered in Chapter 5 (computer simulation study) and Chapter 6 (laboratory experimental study) of this thesis as an application that offers high potential for increasing the thermal mass of lightweight buildings and for renovating existing buildings. Ceiling panels made of plasterboard or clayboard combined with a microencapsulated paraffin wax material are studied. Both passive ceiling panels combined with night-time natural ventilation and active ceiling panels with embedded pipes for night-time cooling are considered. The performance evaluation study concentrates on the application of PCM-plasterboard or PCM-clayboard suspended ceiling for room temperature control and cooling load management during summer-time in office buildings.

PART III: PARAMETRIC STUDY ON PCM ENHANCED THERMAL MASS

In this part is done a parametric study through computer simulations, evaluating the efficiency and potential benefits of the use of PCM-gypsum ceiling panels to enhance the thermal mass of lightweight office buildings. The concept aims at increasing the room temperature control capabilities and improve the cooling load management due to the added by the PCM thermal mass. The effects of several parameters are studied.

Some of the work presented here was utilized in the development of Paper II ('Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels') and Paper III ('Use of PCM-Plasterboard Ceiling Panels for Building Thermal Mass Enhancement, Temperature Control and Peak Load Management in a Continental Mediterranean Climate'), enclosed in Appendix A.

7. Ceiling Panels with Phase Change Material for Building Thermal Mass Enhancement and Cooling Load Management in Office Buildings – parametric study through computer simulations

The main objective of this chapter is to assess, through computer simulations, the efficiency and potential benefits of the use of phase change materials in building materials and components to enhance the thermal mass of lightweight buildings and to improve cooling load management. The evaluation was performed in terms of summertime temperature control, cooling load peak reduction and the shifting of the daily cooling demand to night-time hours.

PCM-gypsum panels (gypsum combined with microencapsulated paraffin wax material) for suspended ceiling installations are considered here as an application that offers high potential for increasing the thermal mass of lightweight buildings and for renovating existing buildings. A single 2-persons office room, located on a middle floor of a lightweight office building which has high standards for insulation and air tightness, was considered in order to assess the performance of the PCM-plasterboard suspended ceiling in cooling mode during summer.

Use of passive ceiling panels combined with night-time natural ventilation were assessed for the moderate summer climate of Copenhagen, Denmark, while active ceiling panels with embedded pipes for night-time cooling were considered for the hot summer climate of Madrid, Spain.

The parametric study deals with the following main concepts and parameters:

- Active vs. passive ceiling panels – climate zone dependence
- PCM melting temperature
- PCM-gypsum thermal conductivity
- Passive vs. active ceiling panels performance in terms of cooling load daily profile and intensity, peak load reduction and shifting to night-time hours, and energy savings potential

7.1 Selection of simulation tools

TRNSYS 17 (Klein et al. 2009) is a complete and extensible simulation environment, used for modeling the transient behavior of multi-zone buildings and their systems, chosen for this study. Due to its modular approach, TRNSYS is extremely flexible for modeling a variety of energy systems in different levels of complexity. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, etc.).

The TRNSYS program includes a graphical interface to drag-and-drop components for creating input files (Simulation Studio), a utility for creating a building input file (TRNBuild), and a program for building TRNSYS-based applications for distribution to non-users (TRNEdit). Extensive libraries of non-standard components for TRNSYS are available commercially from TRNSYS distributors.

The TRNSYS input file, including building input description, characteristics of system components, manner in which components are interconnected, and separate weather data are all generated with a graphical user interface known as Simulation Studio. The envelope for the TRNSYS building is created in TRNBuild interface (incl. orientation, building envelope, and heating and cooling systems) and then represented by a component in the Simulation Studio which makes it possible to have inputs and outputs from the building that is previously created.

The performance of the PCM-gypsum ceiling panels was evaluated using a simulation tool integrated into the numerical simulation environment TRNSYS 17. The TRNSYS component (TYPE 399), developed in Dentel & Stephan (2013), allows to model phase change materials (PCM) in passive and active wall constructions. The TYPE 399 has the possibility to model a temperature dependent heat capacity of the PCM. It is also possible to model a hysteresis effect of the PCM, i.e. some PCM materials have different enthalpy curves for melting and solidification.

7.2 Micro-encapsulated PCM material and PCM-gypsum thermal properties

Due to the passive management of the daily heat gains by the PCM-plasterboard ceiling panels, it is expected that the daily operative temperatures will drift within certain limits. The Category III thermal environmental temperature range of 22-27°C given in EN ISO 15251 was selected as the thermal comfort range for the present study.

From the literature review on PCM used in gypsum and plasterboard composites, given in Chapter 4, it was shown that in building thermal mass enhancement applications PCMs' melting temperature should be in the comfort temperature range. PCMs with a phase change temperature in the range of 18 - 30°C were investigated in the different studies to meet the need of thermal comfort. In Table 7-1 are given the PCM melting temperature ranges investigated in literature and proven successful for use in building thermal mass enhancement applications.

Table 7-1: PCM fusion temperature for building thermal mass enhancement – from literature review

Study	PCM fusion temperature
Schossig et al. (2005)	23°C & 26°C
Kendrick & Walliman (2007)	21°C, 22°C & 23°C
Voelker et al. (2008)	25-28°C
Oliver (2012)	26°C
Koschenz et al. (2004)	21-24°C
Kalz et al. (2007)	18-26°C

The micro-encapsulated paraffin selected for the present study was BASF Micronal® PCM type DS 5040X with a melting temperature of 23°C [18]. Data on the thermal properties of that PCM are given in Table 7-2. In order to evaluate the effect of melting temperature on the performance of the ceiling panels, the same thermal properties were assumed for PCM with melting temperatures of 21°C and 26°C. The three PCMs with different fusion temperature were used in the parametric study to examine the most suitable material in terms of temperature control and cooling load management.

Due to the incorporation of the micro-encapsulated PCM material in gypsum, data on the thermal properties of the PCM-gypsum composite was required. Data for the simulations was obtained from BASF (personal communication), based on an incorporation of 26% of micro-encapsulated PCM in the gypsum. In previous experimental studies on PCM plasterboards has been shown that gypsum can be combined with up to 30% by weight of PCM without the need of reinforcement of the plasterboard, with up to 45% by weight of PCM when the board structure is reinforced with some additives, and with up to 60% by weight in wallboard composites. In the present study, PCM-gypsum for use in conventional plasterboards without the need of reinforcement was assumed.

Table 7-2: Thermal properties of PCM materials

Material	PCM23	PCM21	PCM26
Melting range [°C]	21-25	19-23	24-28
Fusion temp. [°C]	23	24	26
Specific latent heat [kJ/kg]	110	110	110
Density [kg/m^3]	980	980	980
Thermal conductivity [W/mK]	0.14	0.14	0.14

The specific heat capacity as a function of temperature, for the PCM-gypsum composite with PCM23 micro-encapsulated paraffin is shown in Figure 7-1, (Source: BASF). For the composite materials with PCM21 and PCM26 paraffin were assumed identical thermal properties, except that the melting and solidification curves are shifted to lower (for PCM21) or higher (for PCM26) temperature ranges, Figure 7-1.

In addition to the specific heat capacity, adding micro-encapsulated PCM to the gypsum will modify also the thermal conductivity and density for the resultant composite material. For estimating the resultant conductivity and density of the PCM-gypsum composite, Eq. 7.1 and Eq. 7.2 were used to determine these properties theoretically. The properties of pure gypsum and microencapsulated PCM, and of the PCM-gypsum composite, used in the parametric study, are given in Table 7-3.

$$\lambda_{\mathrm{PCM-gypsum}} = \lambda_{\mathrm{PCM}} \cdot \text{"}\%_{\mathrm{PCM}}\text{"} + \lambda_{\mathrm{gypsum}} \cdot (1 - \text{"}\%_{\mathrm{PCM}}\text{"})\ \ \mathrm{W/mK} \quad (7.1)$$

$$\rho_{\mathrm{PCM-gypsum}} = \rho_{\mathrm{PCM}} \cdot \text{"}\%_{\mathrm{PCM}}\text{"} + \rho_{\mathrm{gypsum}} \cdot (1 - \text{"}\%_{\mathrm{PCM}}\text{"})\ \ \mathrm{kg/m^3} \quad (7.2)$$

Table 7-3: Thermal properties PCM-gypsum composite (26% mass content of PCM)

Material type	**Gypsum**	**Micro-encapsulated PCM**	**PCM-gypsum composite**
Conductivity λ [W/mK]	0.47	0.14	0.384
Density ρ [kg/m^3]	1300	980	1217

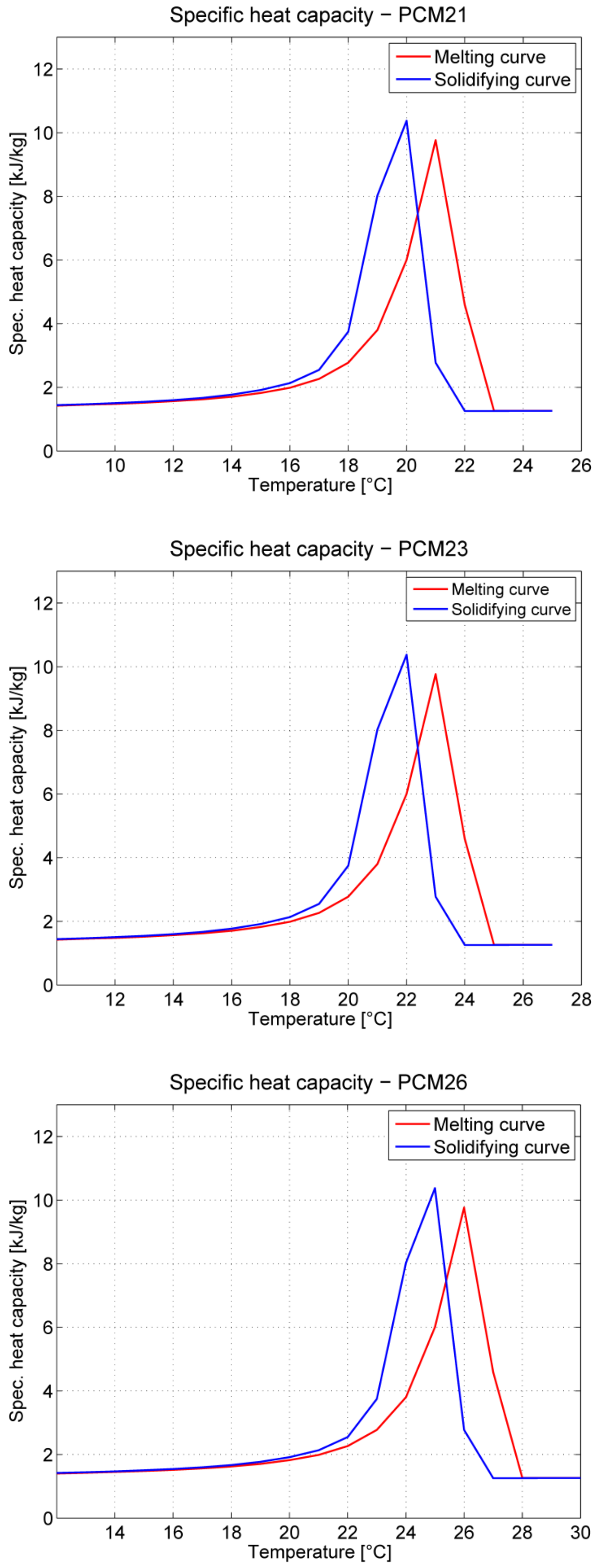


Figure 7-1: Specific heat capacity of PCM-gypsum composite with PCM21, PCM23 and PCM26 micro-encapsulated paraffin (Source: BASF)

7.3 PCM-gypsum ceiling panels design

The PCM-gypsum panels for suspended ceiling installation, considered in the present study, were made of gypsum combined with a micro-encapsulated paraffin wax material. Both passive ceiling panels combined with night-time natural ventilation and active ceiling panels with embedded pipes for night-time cooling were considered in the performance evaluation, Figure 7-2.

a) Passive Panel **b) Active Panel**

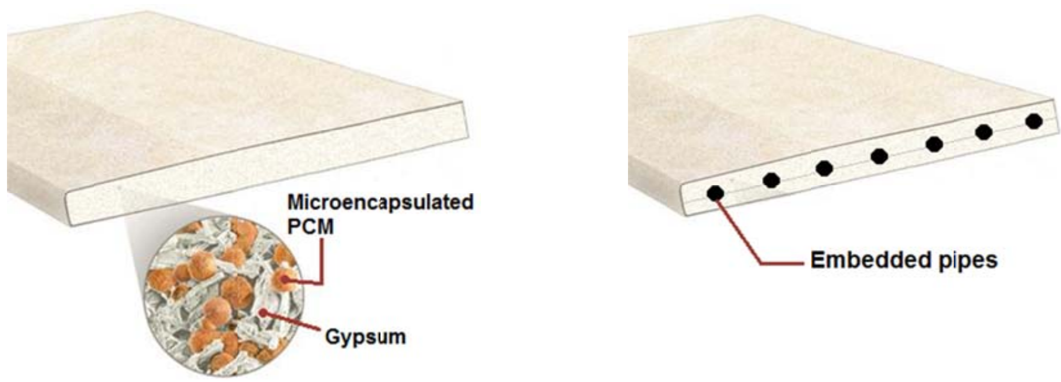


Figure 7-2: PCM-gypsum ceiling panels

The simulation study was based on the use of 2.5 cm thick ceiling panels and an incorporation of 26% by weight of micro-encapsulated PCM in the PCM-gypsum composite. The resultant total capacity per square-meter panel was 845 kJ/m^2 (235 Wh/m^2) heat of fusion.

In the work of Neeper (2000), the author studied the thermal dynamics of a PCM wallboard under daily temperature variations, and showed that the daily storage capacity is limited to about 300-400 kJ/m^2. For the present parametric study, PCM-gypsum panels with much higher storage capacity were used. The high storage capacity allowed a detailed investigation of the effect of different parameters and cooling load profiles on the utilization of the added by the PCM thermal mass in the ceiling panels.

The embedded pipes system in the active ceiling panels was built of 10 mm PEX pipe with 10 cm pipe spacing, installed in the center of the panels. The pipe thickness was 1 mm and the thermal conductivity of the pipe material was assumed 0.4 W/mK.

7.4 Climate data and enhanced thermal mass benefits

Two different climatic locations were selected in the simulation study, for evaluating the potential benefits of building thermal mass enhancement through the use of PCM in building materials.

Use of passive ceiling panels combined with night-time natural ventilation was assessed for the moderate summer climate of Copenhagen, Denmark. At that climatic location, low night-time outdoor ambient temperatures are often present, which gives the possibility of using passive cooling by natural night-time ventilation. Excess heat gains stored in the PCM-gypsum ceiling panels during daytime can be extracted during night-time in order to shift and reduce peak cooling loads and to reduce energy consumption by the use of passive cooling. In addition to peak load shredding and energy savings, the concept can provide efficient means for room temperature control.

Active ceiling panels with embedded pipes for night-time cooling were considered for the hot summer climate of Madrid, Spain. Even though that climatic location has high diurnal temperature variation, due to the high minimum ambient temperatures and their short presence during few hours at night, passive ventilative cooling of the building during night-time cannot be used to reduce and delay peak cooling demand. The heat gains stored in the PCM-gypsum ceiling panels during the day were removed at night by means of an embedded water pipe system, like in conventional TABS system. The temperature of the cooling water could be close to the PCM fusion temperature (close to the daily average room temperature), which gives high potential for using renewable energy sources (ground source heat pumps, ground heat exchangers, etc.).

Although, the active system does not provide energy savings due to the utilization of passive cooling techniques, the concept provides further benefits. Due to the active utilization of the thermal mass added by the PCM-gypsum ceiling panels, cooling loads can be reduced and shifted to off-peak hours. There is no need to instantly supply the cooling demand of the space to the ceiling panels but instead it can be transferred with a time shift and at power levels which differ from the actual demand. Shifting of the daily cooling loads to night-time allows operation at a reduced night-time electricity price, and the concept could benefit from time-of-use electricity tariffs. Additionally, the cooling system does not have to be designed to cover the maximum thermal load and the reduced capacity of the refrigeration equipment provides further economies.

To assess the above mentioned benefits, the passive (for Copenhagen) and active (for Madrid) ceiling panels' performance is evaluated for a typical summer week in July. The weather data used is from ASHRAE IWEC (International Weather for Energy Calculations) weather data files for the corresponding two locations. In Table 7-4 are summarized the outdoor temperature variations for the examination period.

Table 7-4: Climate data for typical summer week in July		
Location	**Copenhagen (DK)**	**Madrid (ES)**
Max daily temperature	21.9	36.0
Min daily temperature	10.5	16.1
Average daily temperature	16.4	26.5

7.5 Simulation models

A reference building model was developed in order to study the proposed concept of PCM-gypsum ceiling panels. The indoor space simulated was a 2-persons office room, located on a middle floor of a lightweight office building which has high standards for insulation and air tightness. The office space had a total floor area of 22.7 m^2 and a volume of 68.1 m^3. The only exterior wall of the office had a glazed surface area of 4.5 m^2, and was facing south in order to evaluate extreme summer conditions. The layout of the office is shown in Figure 7-3 and Figure **7-4**, while building envelope data is given in Table 7-5. As can be seen from the data given in the table, the building had a relatively low thermal mass; the exterior walls were built of highly insulated lightweight panels, and the interior walls were built of gypsum panels with acoustic insulation. The only thermally heavy material in the structure was located in the building structural slabs made of reinforced concrete.

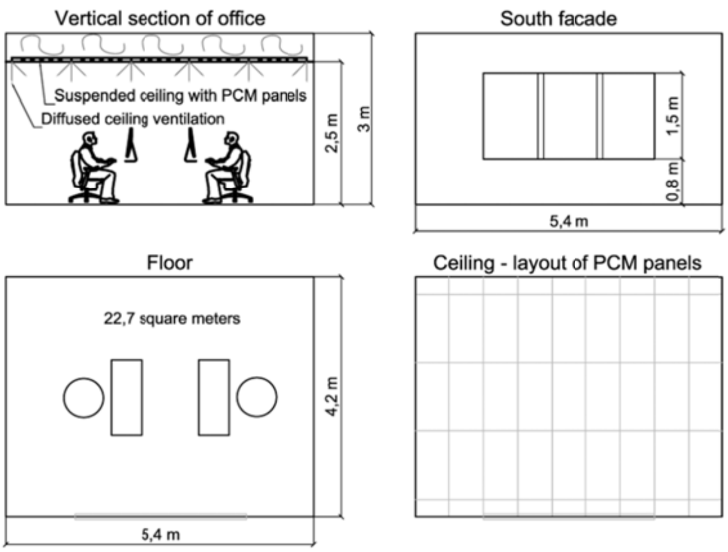
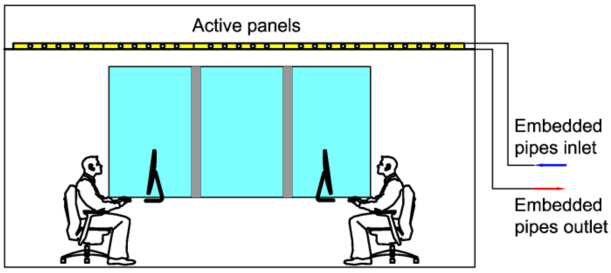


Figure 7-3: Office Layout

The office room was equipped with external solar shading that was controlled by the incident solar radiation during the day (9 a.m. – 7 p.m.). When the incident solar radiation on the window pane exceeded 300 W/m^2, a solar shading factor of 0.8 was added to the glazing.



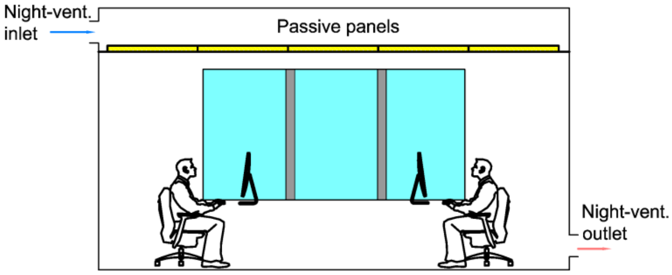


Figure 7-4: Office room with passive and active PCM-gypsum ceiling panels

The internal heat gains in the office were assumed to be 26.5 W/m^2 (100% convective gains) and comprised of 2 occupants, lighting and equipment. The loads were assumed to be 100% present during the daily occupancy hours (9 a.m. - 5 p.m.). Since the PCM-gypsum ceiling panels should be considered as a type of radiant system, when evaluating their performance it would be more beneficial to account the thermal loads in the space as convective and radiant part, which would result in higher system efficiency in terms of thermal performance. However, for the comparative approach of the parametric study, that issue should not have affected the tendency of the results, and in addition it can be regarded as a more conservative approach towards the ceiling panels' thermal performance evaluation.

Table 7-5:: Building envelope data

Building component	Material (in to out)	T [m]	λ [W/mK]	Cp [J/kgK]	ρ [kg/m^3]	U-value [W/m^{2}K]
External wall	Plaster	0.013	0.45	1000	1600	**0.1**
	Insulation	0.35	0.037	800	35	
	Ext. cladding	0.008	0.35	800	1050	
Floor/ Ceiling	Plywood	0.01	0.15	1200	800	**1.5**
	Light concrete	0.05	0.85	1000	500	
	Heavy concrete	0.2	2.3	1200	2400	
Internal wall	Plaster	0.026	0.45	1000	1600	**1.5**
	Insulation	0.02	0.045	800	21	
	Plaster	0.026	0.45	1000	1600	
Windows	**Solar transmission 0.4**				**U_{tot} [W/m^{2}K] 0.6**	

The PCM ceiling panels provided the main cooling capacity of the HVAC system. Suspended ceiling installation was considered (Figure 7-3 and Figure **7-4**). The space created between the suspended ceiling and the structural slab of the building was used as a plenum, where the ventilation air was first supplied to the building and then directed into the office space through the gaps between the ceiling panels. The ventilation system, operated daily from 8 a.m. to 5 p.m., was used to provide fresh outdoor air, and as a supplementary cooling system for the PCM ceiling panels. The ventilation flow rate used was determined according to EN ISO 15251, for Category I of indoor air quality (in a low polluting office), resulting in 136 m^3/h ($2h^{-1}$). The supply temperature of the ventilation air was 19°C.

Two strategies for discharging the thermal energy stored in the PCM-gypsum ceiling panels were investigated, depending on the climatic location. The first strategy used for the climate of Madrid, was as in a conventional TABS system to discharge the ceiling panels through the embedded pipe system during night-time. For the second strategy used for the climate of Copenhagen, the ceiling panels worked as passive thermal mass and night-time natural ventilation was used to discharge the PCM panels. The control of night-time cooling was influenced by the PCM fusion temperature and the thermal comfort boundaries for room temperature variation, and is further discussed during the following steps of the parametric study.

7.6 Effect of PCM fusion temperature on temperature control and thermal mass utilization

To study the effect of PCM fusion temperature on the performance of PCM-gypsum ceiling panels, three PCMs were selected: PCM21, PCM23 and PCM26; where their thermal properties were given in Table 7-2. The performance of the different system configurations were evaluated in terms of temperature control and stored thermal energy.

Due to the different night-time cooling strategies and control principle, and the different level of climate dependence, the passive and active ceiling panels' performance were considered separately from one another. At the end, a general conclusion was drawn on the most suitable phase change temperature, and its dependence on type of ceiling panel and night-time cooling strategy.

7.6.1 Passive PCM-gypsum ceiling panels – effect of fusion temperature

For the moderate summer climate of Copenhagen, passive PCM-gypsum ceiling panels and cooling by night-time natural ventilation was investigated. The control of night-time natural ventilation was made according to PCM fusion temperature considering also the thermal comfort limits on indoor temperature variation in the office space.

Night-time natural ventilation with $4h^{-1}$ could be activated from 10 p.m. to 6 a.m. in all the test cases. When PCM21 was used in the ceiling panels, the office space was ventilated as long as all of the following three criteria were fulfilled:

- Outdoor air temperature was 3K or more lower than the indoor air temperature (to ensure sufficient cooling effect by the night-time ventilation)
- Operative temperature in the office was higher than 21°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 18.5°C (0.5K lower that the lower boundary of the PCM21 melting temperature range)

When PCM23 was used in the ceiling panels, all of the following three criteria had to be fulfilled for night-time ventilation operation:

- Outdoor air temperature was 3K or more lower than the indoor air temperature (to ensure sufficient cooling effect by the night-time ventilation)
- Operative temperature in the office was higher than 21°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 20.5°C (0.5K lower that the lower boundary of the PCM23 melting temperature range)

And at last, when PCM26 was used in the ceiling panels, the following three criteria were placed for controlling the night-time natural ventilation:

- Outdoor air temperature was 3K or more lower than the indoor air temperature (to ensure sufficient cooling effect by the night-time ventilation)
- Operative temperature in the office was higher than 21°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 23.5°C (0.5K lower that the lower boundary of the PCM26 melting temperature range)

To evaluate the performance, in terms of temperature control, of the PCM-gypsum ceiling panels with different PCM fusion temperature, the indoor operative temperature achieved was selected as the evaluation parameter. In Figure 7-5 the operative temperatures indoors for three consecutive days are shown, for suspended ceiling with night-time ventilative cooling and ceiling panels with PCM with different fusion temperature. Additionally, for the sake of fare comparison, the space sensible heat gains in the office, for the different case studies, are shown in Figure 7-6.

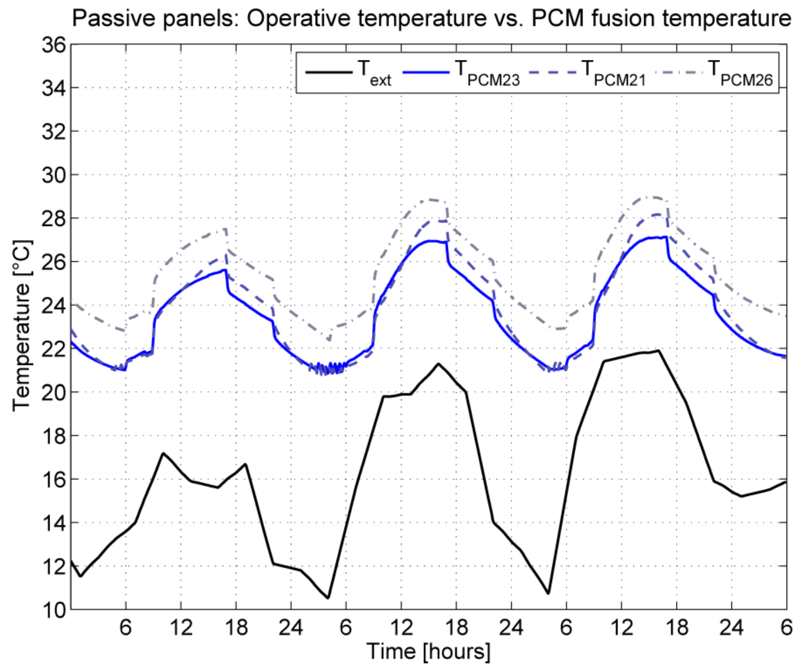


Figure 7-5: Operative temperature in the office, for different PCM fusion temperatures

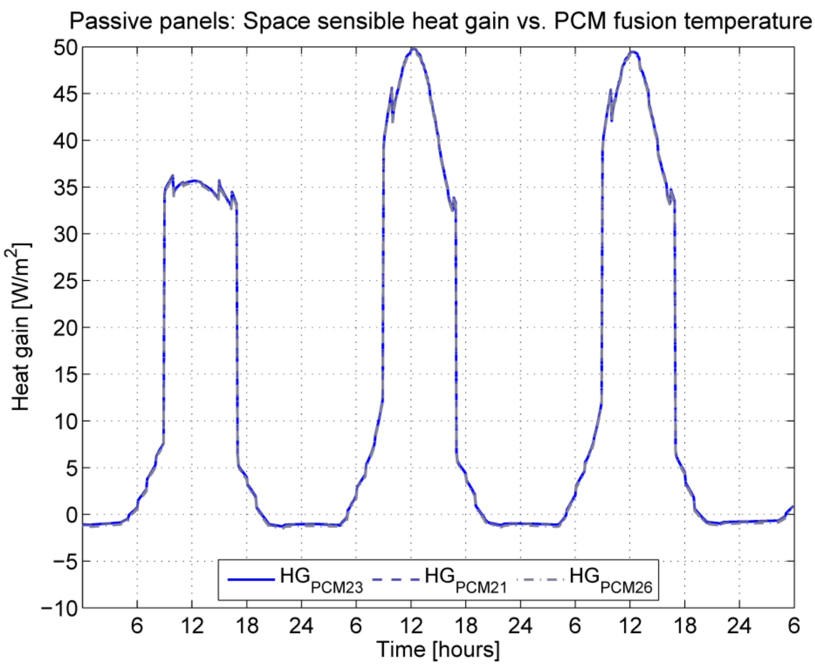


Figure 7-6: Office sensible heat gain for different PCM fusion temperatures

The results show that the same space sensible heat gain resulted for the three case studies, which allowed a fair comparison of the ceiling panels performance. The resulted space sensible heat gains for the three case studies were identical due to the fact that the building is highly insulated with low infiltration rate and the resultant effect of transmission and infiltration heat gains is minor between the different case studies. The maximum office heat gain reached about 50 W/m^2, where the peak occurring at noon due to the office façade facing south direction. The total cooling load of the office resulted in up to 354 Wh/m^2.

Depending on the PCM melting temperature range, different indoor thermal comfort was achieved, e.g. for the ceiling panels with PCM23 the indoor operative temperature varied between 21°C and 27°C during the hours of occupancy (9 a.m. – 5 p.m.). When PCM with higher melting temperature was used (PCM26), higher operative temperatures occurred (23-29°C). However, using PCM with lower melting temperature (PCM21), did not result in lowering the office operative temperature (21-28°C). This can be attributed to the fact that the night-time ventilative cooling was limited to office temperatures of 21°C, which prevented the complete solidification of the PCM21 material in the ceiling panels and respectively to a limited storage capacity available on the following day.

The results did not confirm completely the expectation that the indoor operative temperature range will be directly dependent on the PCM melting temperature: the lower PCM fusion temperature should result in lower surface temperature of the ceiling panels, higher heat absorbing rate and respectively lower operative temperature indoors. As already mentioned, due to the thermal comfort limits on night-time ventilative cooling, using PCMs with somehow lower melting temperature (as in the case of PCM21), will not be an efficient solution. To confirm these observations, the ceiling panels surface temperature and surface heat flux variations are shown in Figure 7-6 and Figure **7-7**.

The effect of added by the PCM thermal mass in the ceiling panels can be clearly seen by the dampened amplitude of the daily variation of ceiling's surface temperature (about 2-3K) in comparison to room temperature variation (about 6K), for the cases with PCM23 and PCM26. As already mentioned, the ceiling panels with PCM21 have shown a limited storage capacity, due to the insufficient night-time cooling limited by the thermal comfort restriction. That shortage in storage capacity results in daily variation of the ceiling's surface temperature of up to 6K, which is only slightly lower that the office operative temperature variation of about 7K.

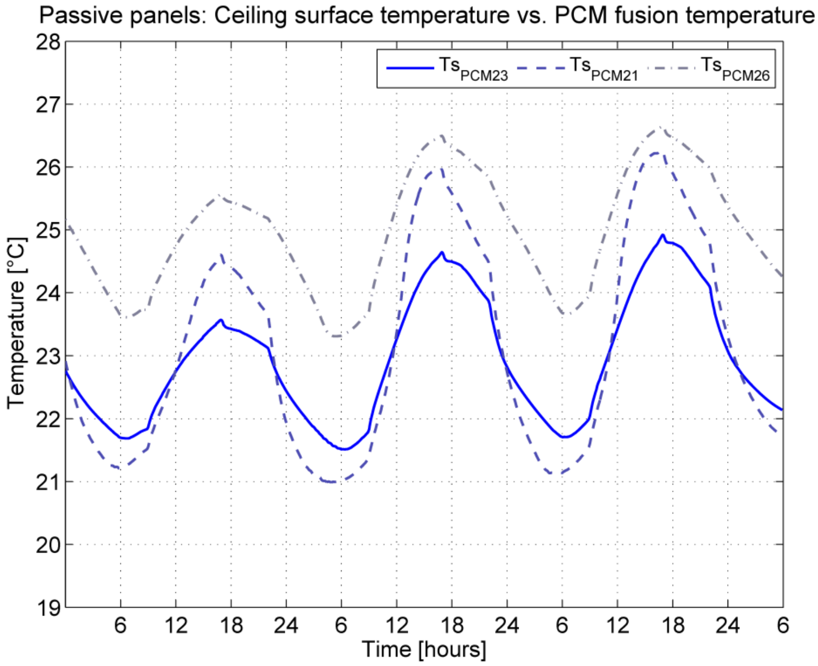


Figure 7-7: Ceiling panels surface temperature for different PCM fusion temperatures

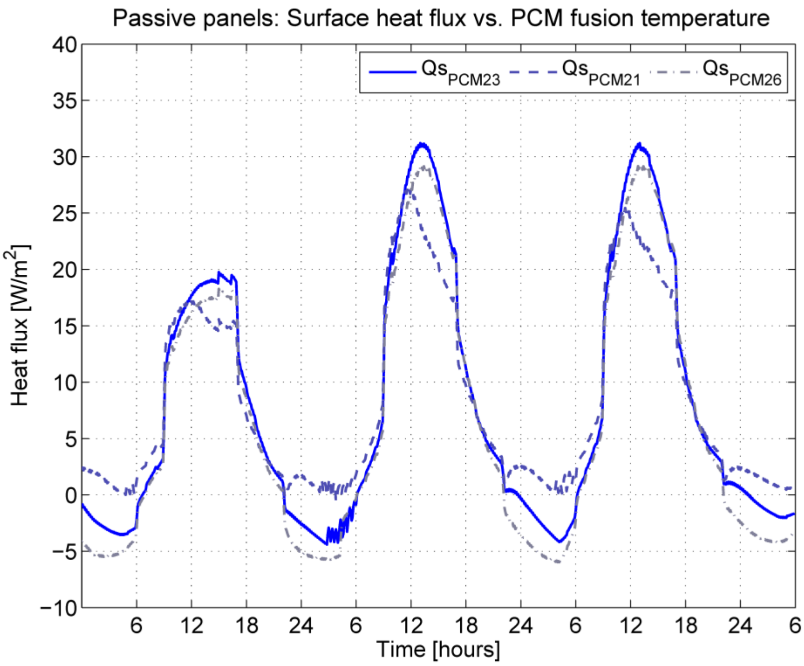


Figure 7-8: Ceiling panels surface heat flux for different PCM fusion temperatures

The surface heat flux on the ceiling panels can be used as an efficient indicator of the thermal mass utilization of- and provided cooling capacity by- the PCM-gypsum panels. The highest surface heat flux, during the hours of occupancy (9 a.m. – 5 p.m.), resulted for panels with PCM23 (maximum value of about 32 W/m^2) which slightly outperformed the panels with PCM26 (maximum value of about 29 W/m^2). For the panels with PCM21 a maximum ceiling surface heat flux of about 26 W/m^2 was achieved and there is a sharp decrease in the surface heat flux after the first 2-3h, indicating the complete utilization of the PCM in the ceiling.

Since the main objective of the PCM-gypsum ceiling panels was to store the excess heat gains in daytime for subsequent night-time extraction, the energy stored in- and discharged from- the ceiling panels may be used as one of the main system performance indicators. In Figure 7-9, the stored thermal energy in the ceiling panels during the hours of occupancy is shown for different fusion temperatures of the phase change material. The highest amount of stored in the ceiling thermal energy was achieved for panels with PCM23 with up to 3.6kWh (159 Wh/m^2), followed by the panels with PCM26 (2.8 kWh, 123 Wh/m^2) and PCM21 (2.5 kWh, 110 Wh/m^2).

As noted above, when the night-time natural ventilative cooling principle was used, very little of the storage capacity, of the ceiling panels with PCM21, was utilized, as, due to the thermal comfort criteria restriction on the night-time ventilative cooling, the lowest indoor operative temperature at night was higher than the lower boundary of the melting temperature range of the PCM material. For ceiling panels with PCM26, although sufficient storage capacity was available, due to the high melting temperature of the PCM material that storage capacity was activated at high room operative temperatures, out of the thermal comfort temperature range. As a result, many hours with overheating were encountered for ceiling panels with PCM21 and PCM26. PCM23 material, with fusion temperature of 23°C and melting range 21-25°C, proved to be most suitable solution in terms of temperature control and thermal mass utilization.

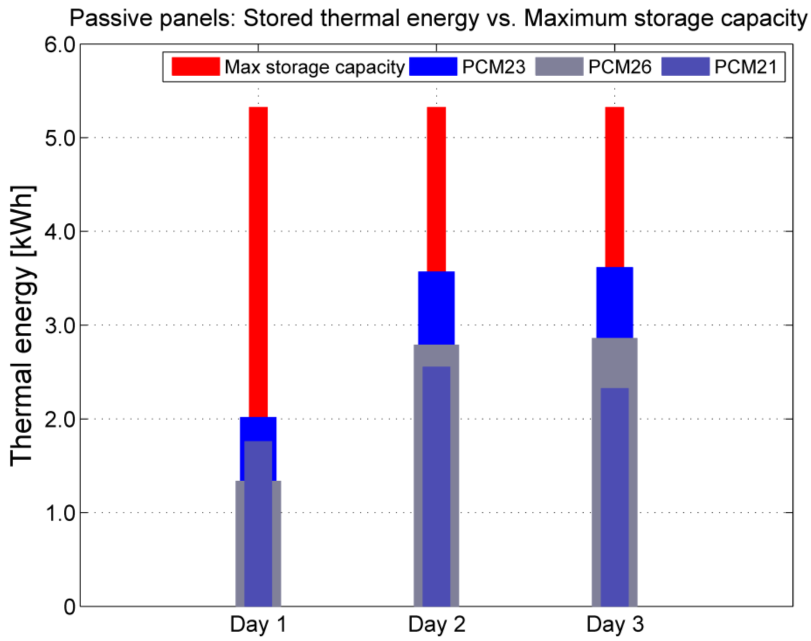


Figure 7-9: Stored thermal energy in the ceiling panels for different PCM fusion temperatures

7.6.2 Active PCM-gypsum ceiling panels – effect of fusion temperature

For the hot summer climate of Madrid, active PCM-gypsum ceiling panels and night-time cooling through the embedded pipes system were used. The control of night-time cooling was done according to the PCM fusion temperature considering also the thermal comfort limits on indoor temperature variation in the office space. Water flow rate of 5 kg/h/m^2 and a 4K temperature difference between supply and return water from the embedded pipes system were used in all three test cases.

By using active cooling by the embedded pipes system, the discharge of the thermal energy stored in the ceiling panels was made independent of the local climatic conditions. Additionally, due to local extraction of the stored thermal energy by the embedded pipes system, less influence on the room operative temperature was expected, when PCMs with low fusion temperature, out of the thermal comfort limit for the office space, were used.

Night-time cooling could be activated from 10 p.m. to 6 a.m. in all the test cases. When PCM21 was used in the ceiling panels, the cooling water circulation through the embedded pipes system was activated as long as the following two criteria were fulfilled:

- Operative temperature in the office was higher than 21°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 20°C (the lower boundary of the PCM21 melting temperature range; due to local extraction of the stored heat)

When PCM23 was used in the ceiling panels, the following two criteria had to be fulfilled for night-time cooling operation:

- Operative temperature in the office was higher than 22°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 21°C (the lower boundary of the PCM23 melting temperature range; due to local extraction of the stored heat)

And at last, when PCM26 was used in the ceiling panels, the following two criteria were placed for controlling the night-time cooling:

- Operative temperature in the office was higher than 22°C (due to thermal comfort limitations)
- The surface (facing the office) temperature of the PCM-gypsum ceiling panels was higher than 24°C (the lower boundary of the PCM26 melting temperature range; due to local extraction of the stored heat)

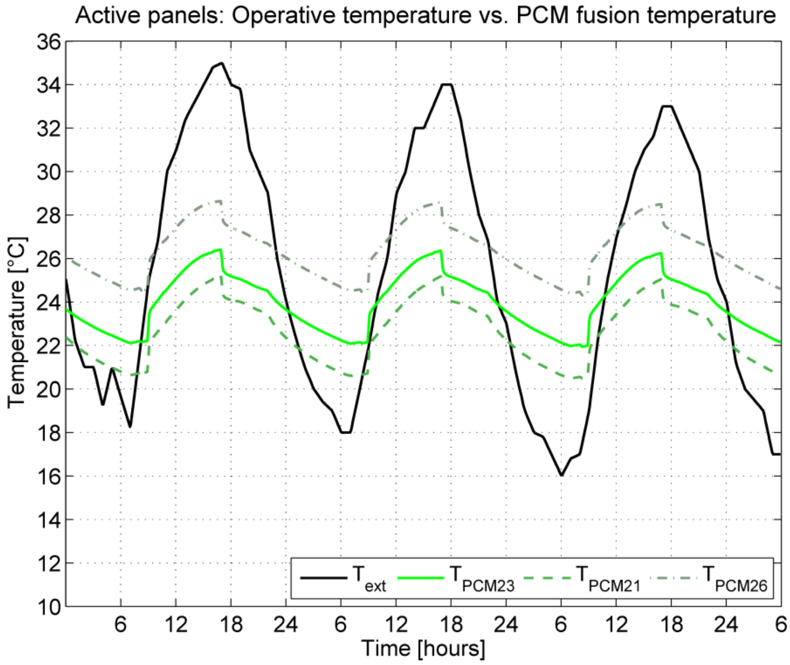


Figure 7-10: Operative temperature in the office, for different PCM fusion temperatures

In Figure 7-10 the operative temperatures indoors for three consecutive days are shown, for suspended ceiling with night-time embedded pipes cooling and ceiling panels with PCM with different fusion temperature. Additionally, for the sake of fare comparison, the space sensible heat gains in the office, for the different case studies, are shown in Figure 7-11.

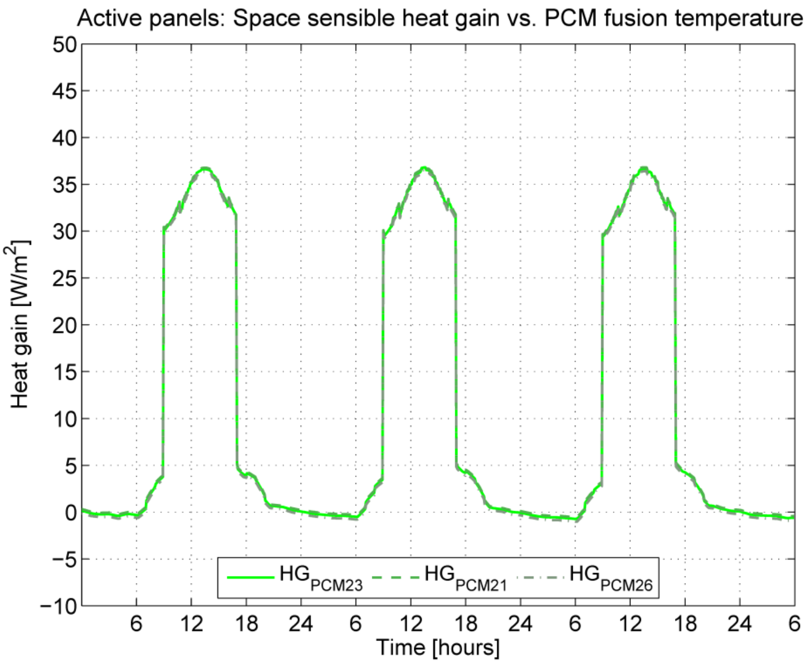


Figure 7-11: Office sensible heat gain for different PCM fusion temperatures

The results show that the same space sensible heat gain resulted for the three case studies, which allowed a fair comparison of the ceiling panels performance. As in the case of passive ceiling panels, the resulted identical space sensible heat gains for the three case studies with active ceiling panels were due to the fact that the building is highly insulated with low infiltration rate. The maximum office heat gain reached about 37 W/m^2, where the peak occurring one hour after noon due to the office façade facing south direction (for the location of Madrid, the peak of sensible heat gain and cooling load respectively occurred one hour later, compared to the location of Copenhagen, which is due to the different position of the sun at that latitude and respectively different peak of the solar heat gain to the space). The total cooling load of the office resulted in up to 269 Wh/m^2.

Depending on the PCM melting temperature range, different indoor thermal comfort was achieved, e.g. for the ceiling panels with PCM21 the indoor operative temperature varied between 21-25.2°C during the hours of occupancy (9 a.m. – 5 p.m.). When PCM with a higher melting temperature was used in the panels, higher operative temperatures indoors occurred, i.e. for PCM23 22-26.3°C and for PCM26 24-28.3°C.

The results confirmed the expectation that the indoor operative temperature range will be directly dependent on the PCM melting temperature: the lower this temperature, the lower the operative temperature indoors. That was somehow different from the results obtained in the case of night-time ventilative cooling and passive ceiling panels. The local heat extraction by the embedded pipes system enabled the complete solidification of the PCM21 material in the ceiling panels, which resulted in having the total storage capacity of the ceiling panels available for the following day. To confirm these observations, the ceiling panels' surface temperature and surface heat flux variations are shown in Figure 7-12 and Figure **7-13**.

The effect of added by the PCM thermal mass in the ceiling panels can be clearly seen by the dampened amplitude of the daily variation of ceiling's surface temperature (about 2.5-3K) in comparison to room temperature variation (about 4.2K), for all the cases. As already mentioned, the ceiling panels with PCM21 have had sufficient storage capacity available, due to the active night-time cooling which opposed the results for passive ceiling panels.

The surface heat flux on the ceiling panels indicates the thermal mass utilization of- and provided cooling capacity by- the PCM-gypsum panels. The highest surface heat flux, during the hours of occupancy (9 a.m. – 5 p.m.), resulted for panels with PCM21 (maximum value of about 26 W/m^2) which slightly outperformed the panels with PCM23 (maximum value of about 25 W/m^2) and the panels with PCM26 (maximum value of about 22 W/m^2).

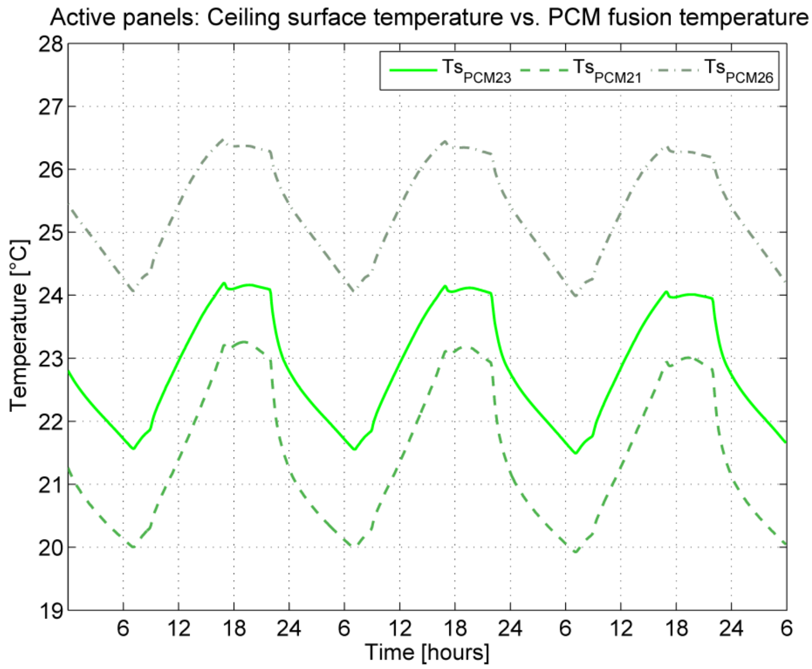


Figure 7-12: Ceiling panels surface temperature for different PCM fusion temperatures

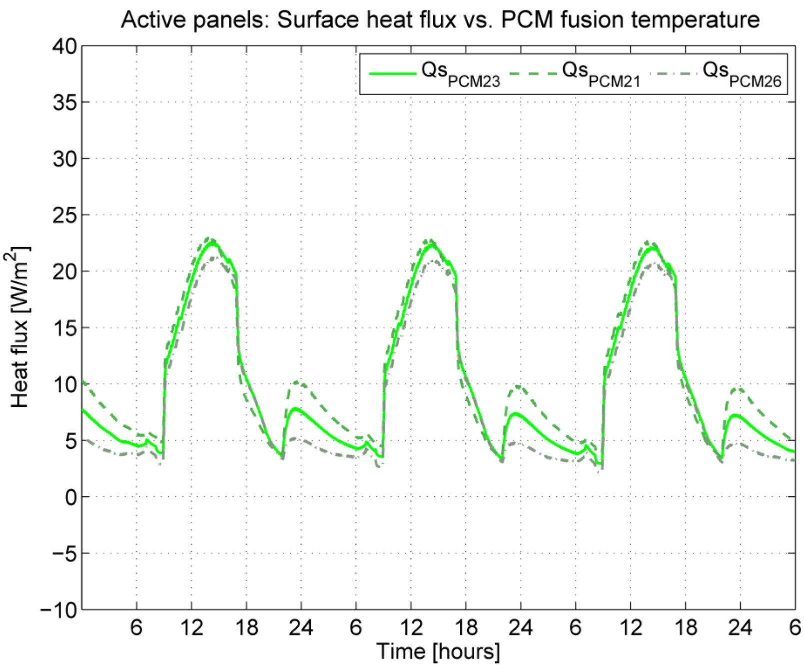


Figure 7-13: Ceiling panels surface heat flux for different PCM fusion temperatures

In Figure 7-14, the stored thermal energy in the ceiling panels during the hours of occupancy is shown for different fusion temperatures of the phase change material. The highest amount of stored in the ceiling thermal energy was achieved for panels with

PCM21 with up to 3.5kWh (154 Wh/m^2), followed by the panels with PCM23 (3.1 kWh, 137 Wh/m^2) and PCM26 (2.4 kWh, 106 Wh/m^2).

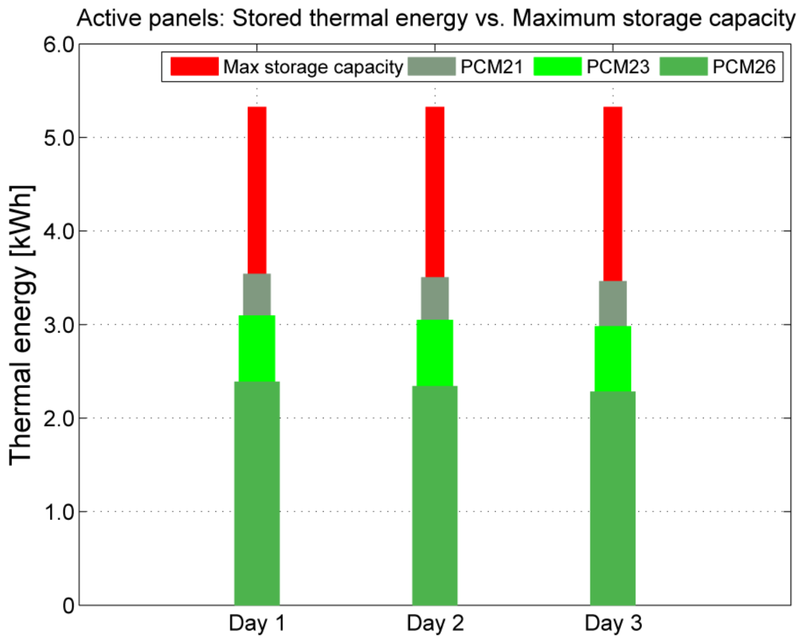


Figure 7-14: Stored thermal energy in the ceiling panels for different PCM fusion temperatures

As noted above, when the night-time embedded pipes cooling principle was used, due to the local cooling of PCM-gypsum panels and the reduced effect on altering the thermal comfort criteria in the early morning hours, the office operative temperature range was directly dependent on the PCM melting temperature. In the case studies with PCM21 and PCM23, the thermal comfort criteria for indoor operative temperature variation of 22-27°C were fulfilled during most of the hours of occupancy. When panels with PCM23 were used the office operative temperatures varied between 22-26.3°C, which showed the best performance in terms of temperature control. For the case of panels with PCM21 the indoor operative temperature varied between 21-25.2°C, resulting in a bit colder temperatures in the first morning hour, however the peak indoor temperature was kept lowest compared to the other two case studies. For ceiling panels with PCM26, due to the high melting temperature of the PCM material, its storage capacity was activated at high room operative temperatures, out of the thermal comfort temperature range. As a result, many hours with overheating were encountered for ceiling panels with PCM26, with daily temperature variations in the range of 24-28.3°C.

Additional benefit of the local heat extraction by the embedded pipes system could be attributed to the lower daily operative room temperature variation achieved (about

4.2K) in comparison to the passive cooling by natural night time ventilation (about 7K), which would result in a better thermal comfort.

In terms of thermal mass utilization, ceiling panels with PCM21 have shown the highest storage capacity utilization. However due to temperature control considerations and the needed for lower temperature of the cooling medium used in the embedded pipes system compared to ceiling panels with PCM23 (due to the lower fusion temperature of the phase change material), the high thermal mass utilization benefit might be outplaced by the insufficient thermal comfort provided and the excess energy used for removing the thermal energy stored in the ceiling panels.

Summarizing the simulation results, similar conclusion as in the cases with passive ceiling panels can be drawn. PCM23 material with fusion temperature of 23°C and melting range 21-25°C would be most suitable solution in terms of temperature control and thermal mass utilization.

7.7 Effect of PCM-gypsum thermal conductivity on thermal performance

Adding micro-encapsulated PCM to gypsum will change adversely the thermal conductivity of the resultant composite material compared to gypsum itself. In the present study, theoretical approach for determining the PCM-gypsum thermal conductivity was used based on the % by weight of PCM and gypsum, resulting in 0.384 W/mK. In other research works, different values of PCM-gypsum conductivities were used, depending on the assumptions made by the authors, mainly in the range of 0.19-0.2 W/mK (Kendrick & Walliman 2007, Kalz et al. 2006).

PCM-gypsum boards with a higher thermal conductivity are likely to perform better, due to the higher rates of absorbing heat during PCM melting and of releasing heat during PCM solidification. In the present section, the effects of half (0.19 W/mK) and double (0.76 W/mK) of the reference PCM-gypsum thermal conductivity were investigated. As it was shown in the simulation results for PCM fusion temperature evaluation, ceiling panels with PCM23 material performed best in terms of room temperature control and storage utilization and this material was used for the thermal conductivity evaluation.

7.7.1 Passive ceiling panels – effect of PCM-gypsum thermal conductivity

The same control of the night-time ventilative cooling was used here, as in the cases of PCM fusion temperature evaluation. The results for office operative temperature, PCM panels' surface temperature and surface heat flux are given in Figure 7-15Figure 7-16Figure 7-17.

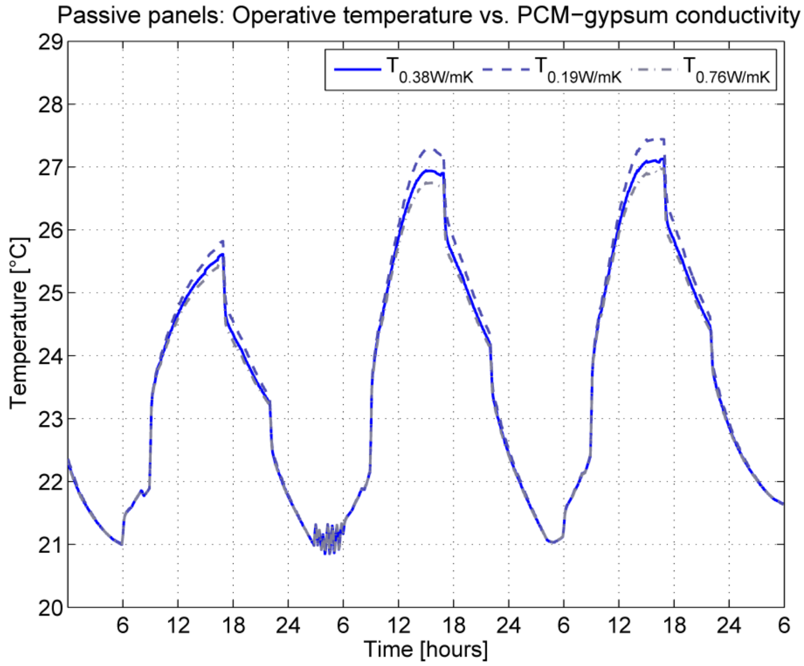


Figure 7-15: Passive panels - operative temperature vs. PCM-gypsum thermal conductivity

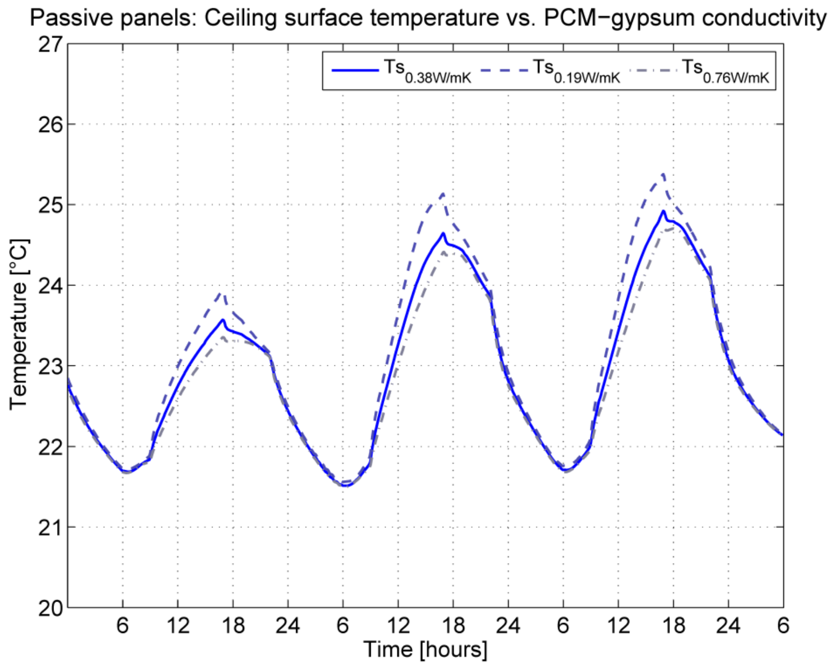


Figure 7-16: Passive panels - surface temperature vs. PCM-gypsum thermal conductivity

Increasing the PCM-gypsum thermal conductivity 0.76 W/mK, resulted in decrease of the peak daily operative temperature with up to 0.2K (from 27°C to 26.8°C) and 0.6K (27.4°C to 26.8°C) compared to conductivities of 0.384 W/mK and 0.19 W/mK.

The ceiling panels' peak surface temperature decreased in identical manner: from 25.1°C to 24.4°C, for thermal conductivity increase from 0.19 W/mK to 0.76 W/mK; and from 24.6°C to 24.4°C, for thermal conductivity increase from 0.384 W/mK to 0.76 W/mK.

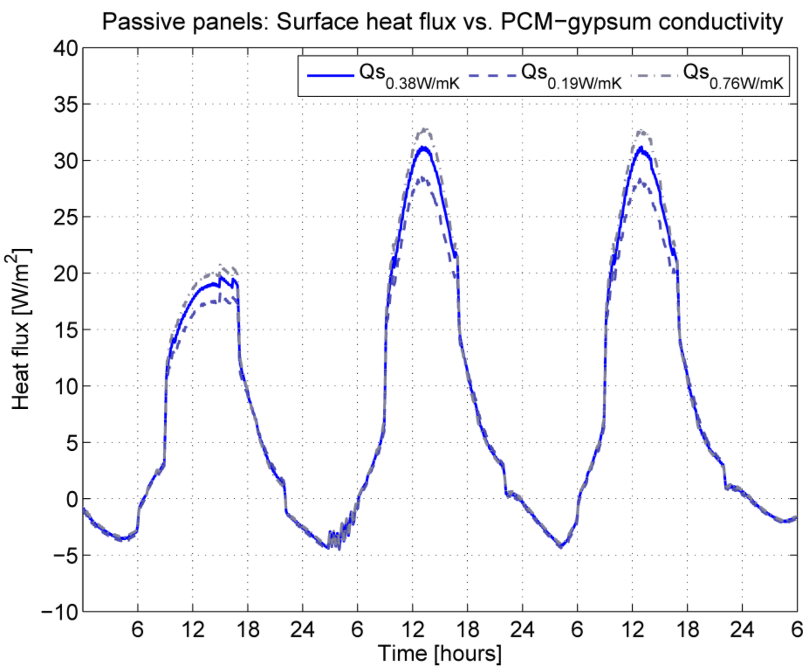


Figure 7-17: Passive panels – surface heat flux vs. PCM-gypsum thermal conductivity

The decrease of the ceiling panels' surface temperature with increase of the PCM-gypsum thermal conductivity resulted in increase of the ceiling panels' surface heat flux and respectively in their heat absorbing rate, i.e. thermal conductivity increase 0.19 → 0.384 → 0.76 W/mK resulted in surface heat flux of 26 → 32 → 35 W/m^2.

As the PCM-gypsum thermal conductivity increases, the speed of heat penetration in the ceiling panels' increases, and more uniform temperature distribution through their thickness is observed, as seen in Figure 7-18 where the temperature distribution in the ceiling panels during a single day is shown. That phenomenon can be attributed to be causing the improved performance in terms of temperature and heat absorption rate.

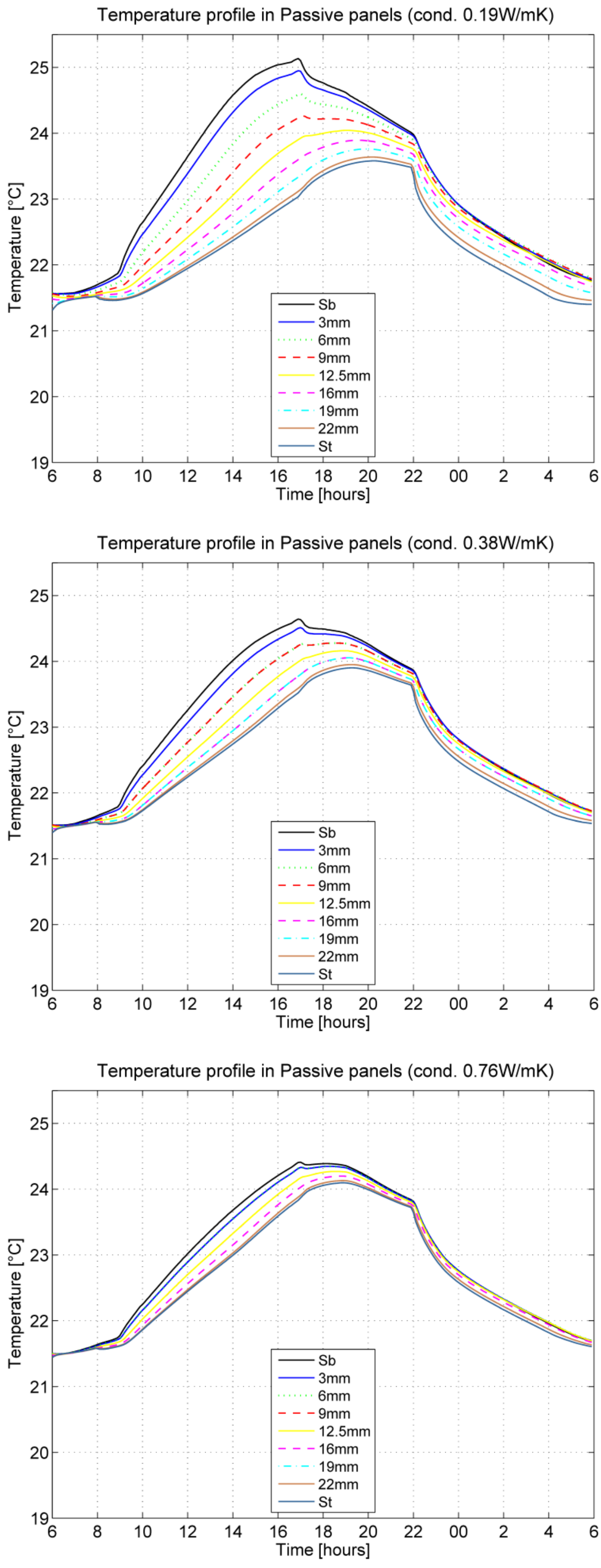


Figure 7-18: Passive panels – temperature profile vs. PCM-gypsum thermal conductivity

The amount of stored thermal energy is shown in Figure 7-19. In relative values, increase of the PCM-gypsum thermal conductivity two and four fold, resulted in maximum increase of the stored thermal energy by 6% and 9% (3.4 kWh → 3.6 kWh → 3.7 kWh).

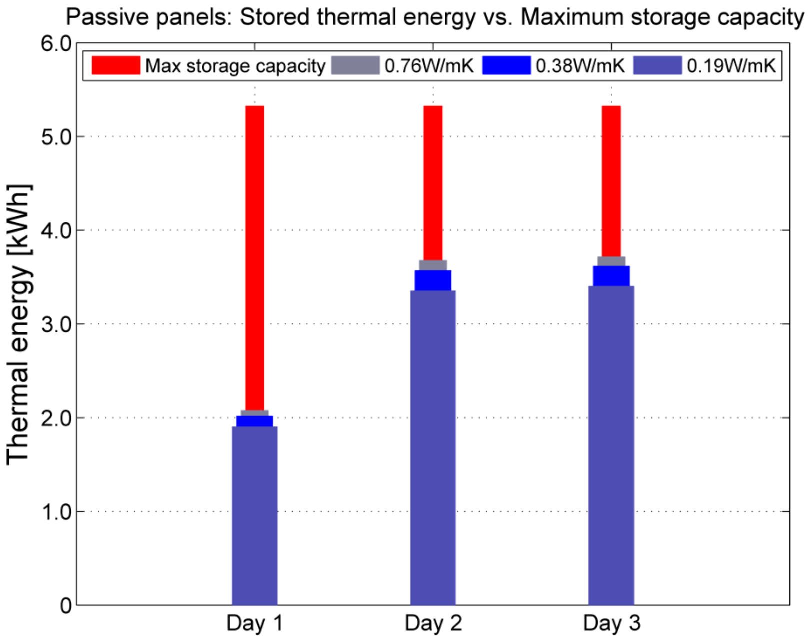


Figure 7-19: Passive panels – stored thermal energy vs. PCM-gypsum thermal conductivity

Summarising the results from the simulation study on the effect of PCM-gypsum thermal conductivity on the passive ceiling panels' thermal performance, there were noticed minor benefits for the studied conductivity range. A tendency of increased benefit of higher thermal conductivity for space cooling loads with higher intensity could be expected, Day 1 benefit compared to Day 2 & Day 3benefit in Figure 7-15, Figure **7-16**, Figure **7-17**, and Figure **7-19**.

7.7.2 Active ceiling panels – effect of PCM-gypsum thermal conductivity

For the PCM-gypsum thermal conductivity evaluation, the same control of the night-time embedded pipes cooling was used, as in the cases of PCM fusion temperature evaluation. The results for office operative temperature, PCM panels' surface temperature and surface heat flux are shown in Figure 7-20,Figure **7-21**, and Figure **7-22**.

Increasing the PCM-gypsum thermal conductivity from 0.19 → 0.384 → 0.76 W/mK resulted in decrease of the peak indoor operative temperature from 26.7 → 26.4 → 26.2°C.

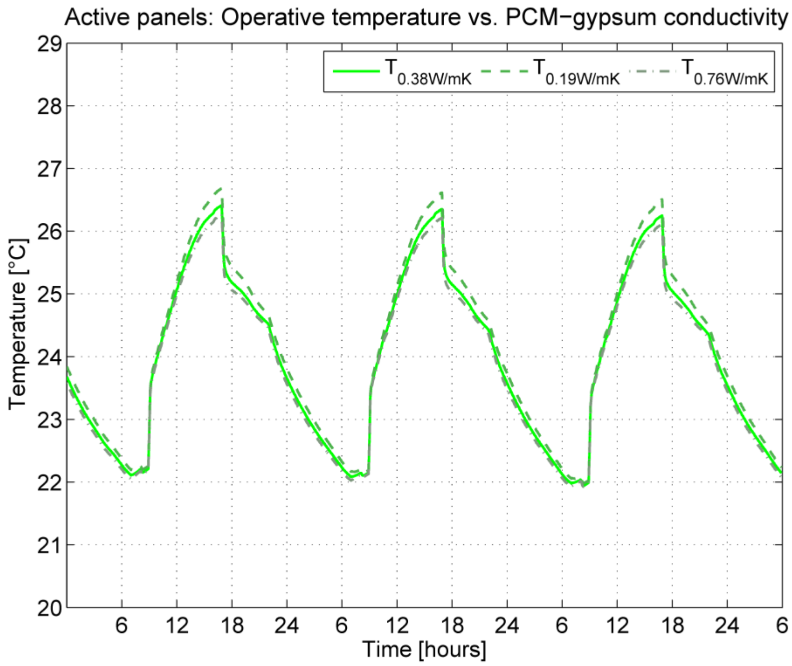


Figure 7-20: Active panels - operative temperature vs. PCM-gypsum thermal conductivity

The ceiling panels' peak surface temperature decreased from 24.6°C to 24.2°C, for thermal conductivity increase from 0.19 W/mK to 0.76 W/mK; and from 24.3°C to 24.2°C, for thermal conductivity increase from 0.384 W/mK to 0.76 W/mK.

Increasing the PCM-gypsum thermal conductivity 0.19 → 0.384 → 0.76 W/mK resulted also in increase of the ceiling panels' surface heat flux 21 → 24 → 27 W/m^2.

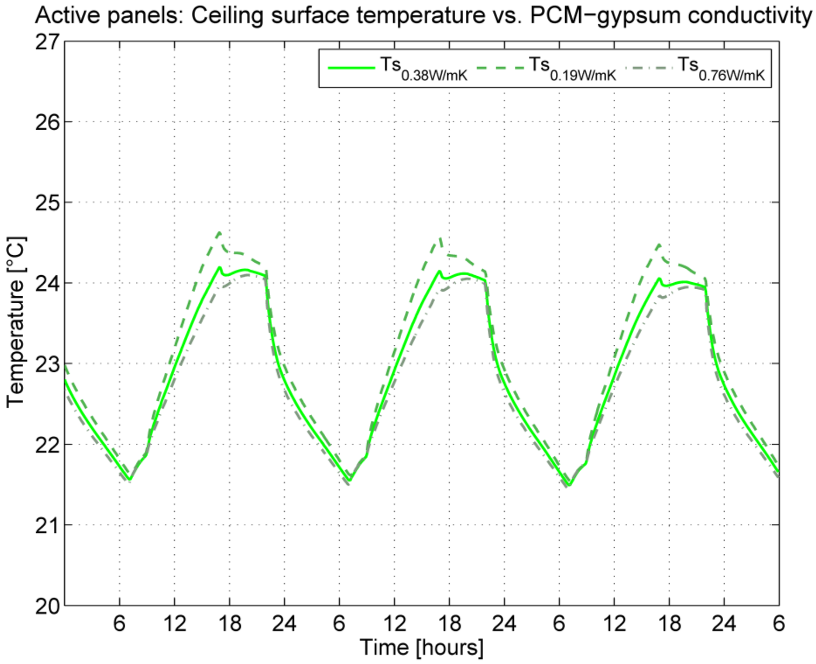


Figure 7-21: Active panels - surface temperature vs. PCM-gypsum thermal conductivity

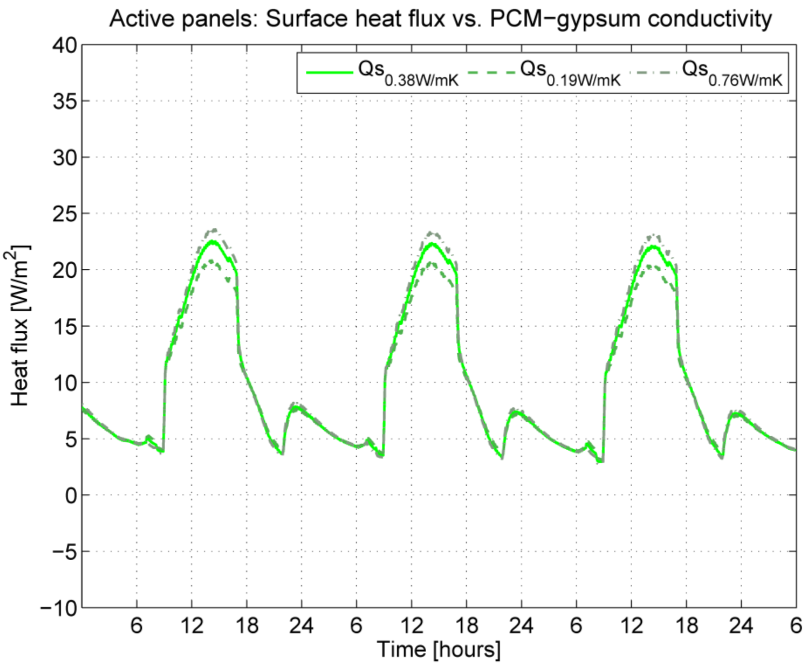


Figure 7-22: Active panels – surface heat flux vs. PCM-gypsum thermal conductivity

In Figure 7-23 is shown the temperature distribution in the ceiling panels during a single day, for different values of the PCM-gypsum thermal conductivity. A more uniform temperature distribution through the ceiling panels' thickness is observed with increase of the panels' thermal conductivity.

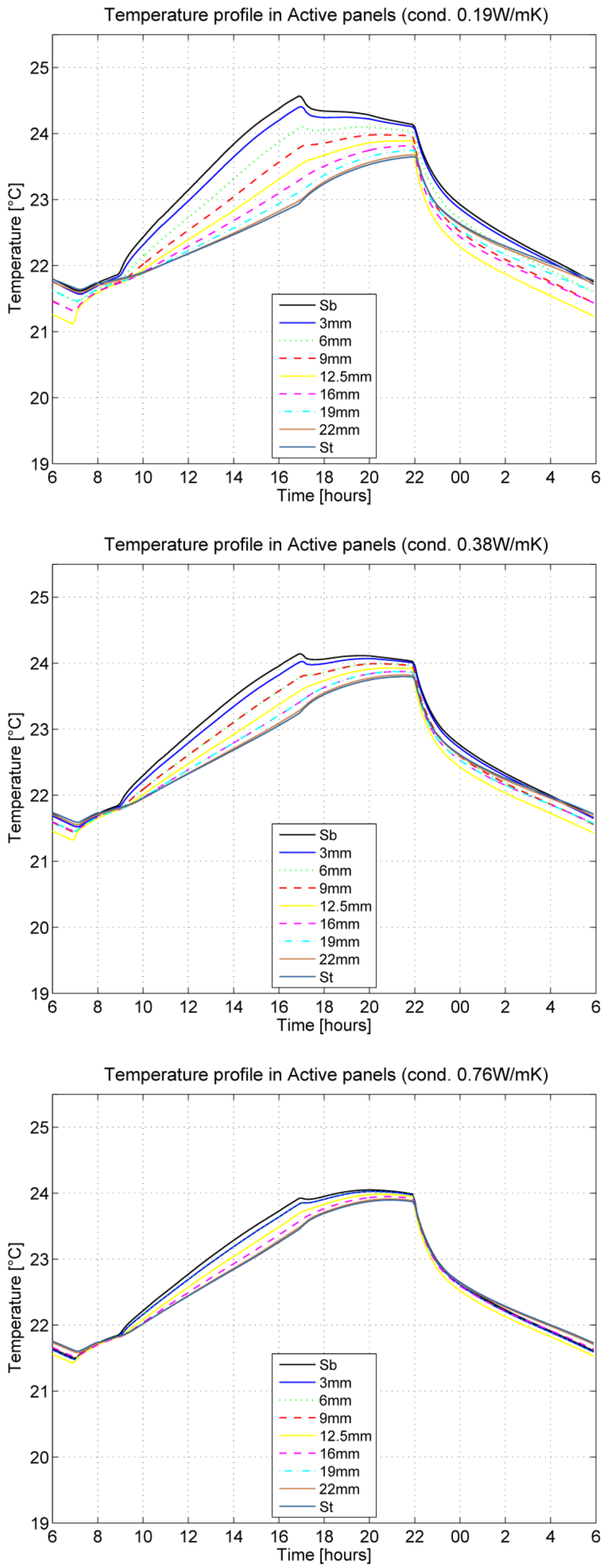


Figure 7-23: Active panels – temperature profile vs. PCM-gypsum thermal conductivity

The amount of stored thermal energy is shown in Figure 7-24. In relative values, increase of the PCM-gypsum thermal conductivity two and four fold, resulted in maximum increase of the stored thermal energy by 3% and 6% (3.0 kWh → 3.1 kWh → 3.2 kWh).

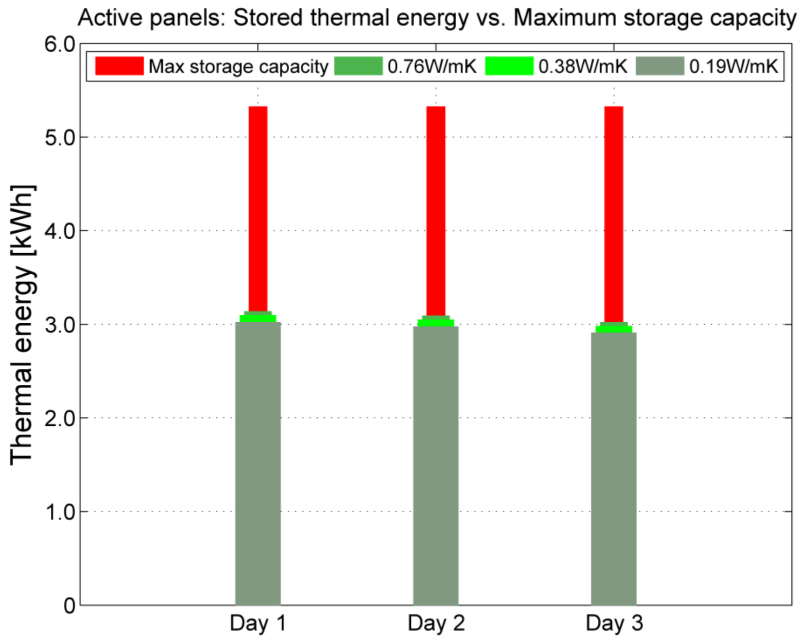


Figure 7-24: Passive panels – stored thermal energy vs. PCM-gypsum thermal conductivity

The results from the simulation study on the effect of PCM-gypsum thermal conductivity on the active ceiling panels' thermal performance, show minor benefits for the studied conductivity range.

A tendency for slight increase of the benefit of higher thermal conductivity for space cooling loads with higher intensity could be expected. That tendency can be seen if the benefits achieved in Day 2 and Day 3 in the case studies for the active panels are compare with the benefits seen in the case studies with passive ceiling panels, where the maximum space heating gains for the cases with active panels have been 37 W/m^2 compared to 50 W/m^2 for the cases with passive panels.

7.8 Cooling load profile and intensity – effect on thermal performance of PCM-gypsum panels

In the following section, the effect the space cooling load profile and intensity on PCM-gypsum ceiling panels' thermal performance is evaluated. The evaluation is performed for panels with PCM23 material and for PCM-gypsum thermal conductivity of 0.384 W/mK. Three different cooling load profiles are generated for both the passive and the active ceiling panels' systems by controlling the external solar shading factor and by that way the solar heat gain to the office space. In addition to room temperature control and stored thermal energy, the energetic performance in terms of peak load shredding and load shifting to night-time hours, as well as energy saving potential are investigated. Although, results for three consecutive summer days are shown in most of the graphs with results, the potential benefit evaluation is performed for Day 2 if not specified precisely in the text.

7.8.1 Passive ceiling panels – effect of cooling load profile on temperature control and thermal mass utilization

The effect of three different cooling load profiles on the thermal performance of passive PCM-gypsum ceiling panels, for the climatic location of Copenhagen, is evaluated. The same building model and HVAC system were used as in the case studies for PCM fusion temperature and PCM-gypsum thermal conductivity evaluation. The only difference is that the comfort limit on night-time ventilative cooling was released to minimum indoor operative temperatures of 20°C. The resultant total maximum daily cooling loads for the three case studies were 307 Wh/m^2 for a profile 'load CB', 344 Wh/m^2 for a profile 'load C', and 386 Wh/m^2 for a profile 'load CA'. The space sensible heat gains are shown in Figure 7-25. For profile 'load C', the maximum space sensible heat gain was 50 W/m^2, while for profiles 'load CB' and 'load CA' the maximum space sensible heat gains were 44 W/m^2 and 57 W/m^2 respectively.

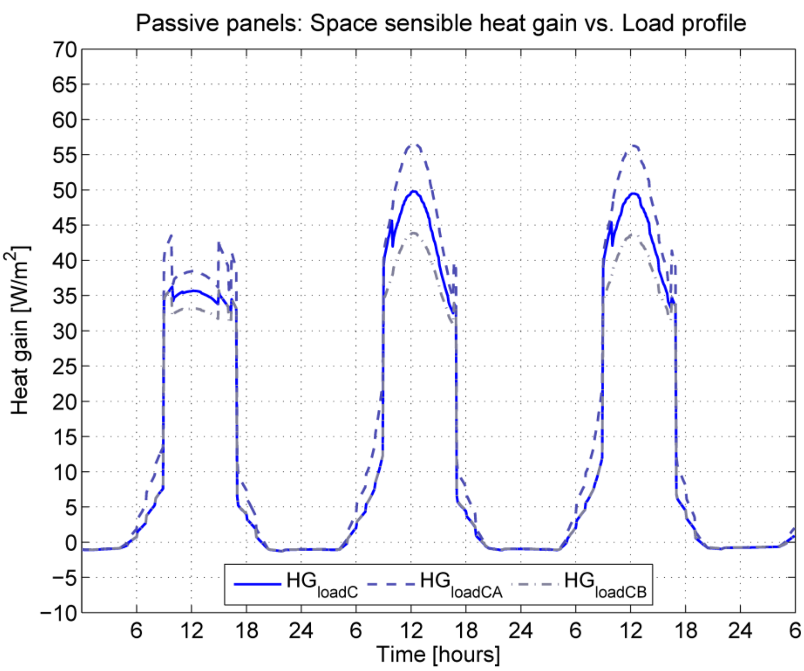


Figure 7-25: Passive panels – space sensible heat gain vs. cooling load profile

The results for office operative temperature, under the different cooling load profiles, are shown in Figure 7-26.

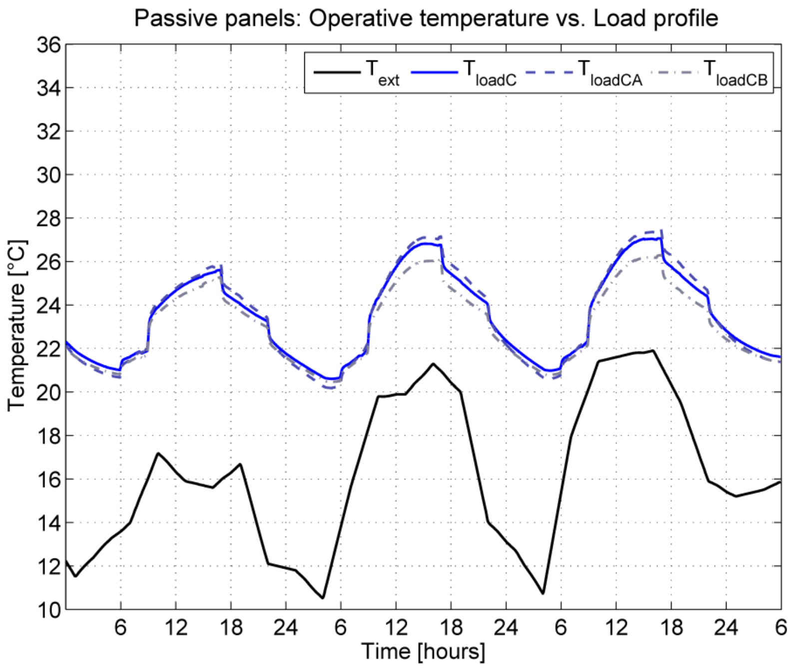


Figure 7-26: Passive panels – operative temperature vs. cooling load profile

Depending on the cooling load profile, different daily operative temperature variation was observed in the three case studies. For profile 'load CB', the resulted daily operative temperature variation during the day was 20.6-26°C (5.4K), for profile 'load C' it was 20.5-26.9°C (6.4K), and for profile 'load CA' 20.2-27.2°C (7K). The passive ceiling panels could in all cases limit the peak of indoor operative temperature below or close to the upper limit for thermal comfort of 27°C. In order to discharge the stored in the ceiling panels thermal energy and pre-cool the office space during night-time, the office space had to be cooled below the lower boundary for thermal comfort of 22°C, down to about 20°C in some of the case studies. However, as can be seen from the results, the indoor operative temperatures could recover to about 22°C in the time period from discontinuing the night-time ventilation to the hours of occupancy (6 a.m. – 9 a.m.). In any case, it is questionable if indoor operative temperatures down to 20°C should be considered discomfortable during the first morning hour in an office building during summertime for population used to a moderate summer climate like Copenhagen.

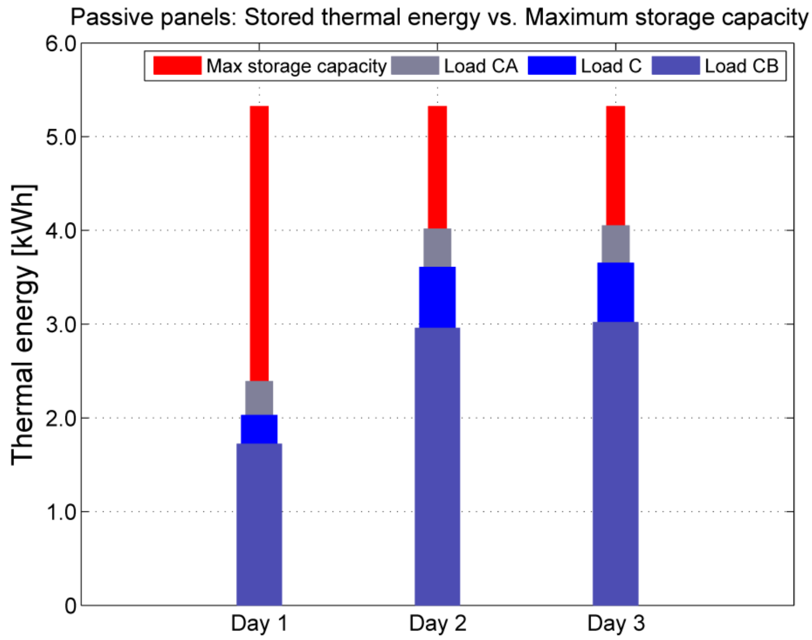


Figure 7-27: Passive panels – stored thermal energy vs. cooling load profile

The stored thermal energy in the passive ceiling panels, under the studied cooling load profiles is given in Figure 7-27. For profile 'load CB', stored thermal energy during the hours of occupancy was 128 Wh/m^2, which is about 42% of the daily cooling load of 307 Wh/m^2, for profile 'load C' it was 159 Wh/m^2 corresponding to 46% of the daily cooling load of 344 Wh/m^2, and for profile 'load CA' 176 Wh/m^2 were stored in the ceiling panels being about 46% of the daily cooling load of 386 Wh/m^2.

7.8.2 Active ceiling panels – effect of cooling load profile on temperature control and thermal mass utilization

The thermal performance of active PCM-gypsum ceiling panels, for the climatic location of Madrid, under three different cooling load profiles was evaluated. The same building model, internal loads and HVAC system were used as in the case studies for PCM fusion temperature and PCM-gypsum thermal conductivity evaluation. The only difference is that the water flowrate for the night-time cooling was increased from 5 $l/h/m^2$ for 'load M' to 7 $l/h/m^2$ for 'load MA' and to 9 $l/h/m^2$ for 'load MB', in order to provide sufficient cooling capacity for discharging the stored in the ceiling panels thermal energy. The resultant total maximum daily cooling loads for the three case studies were 268 Wh/m^2 for a profile 'load M', 318 Wh/m^2 for a profile 'load MA', and 379 Wh/m^2 for a profile 'load MB'. For profile 'load M', the maximum space sensible heat gain was 37 W/m^2, while for profiles 'load MA' and 'load MB' the maximum space sensible heat gains were 45 W/m^2 and 55 W/m^2 respectively. The space sensible heat gains, for the different cooling load profiles, are shown in Figure 7-28.

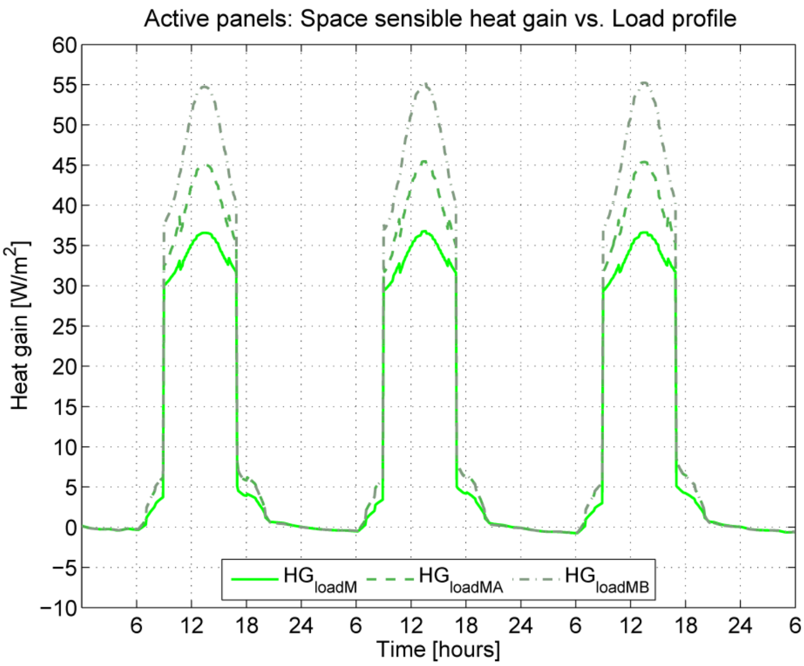


Figure 7-28: Active panels – space sensible heat gain vs. cooling load profile

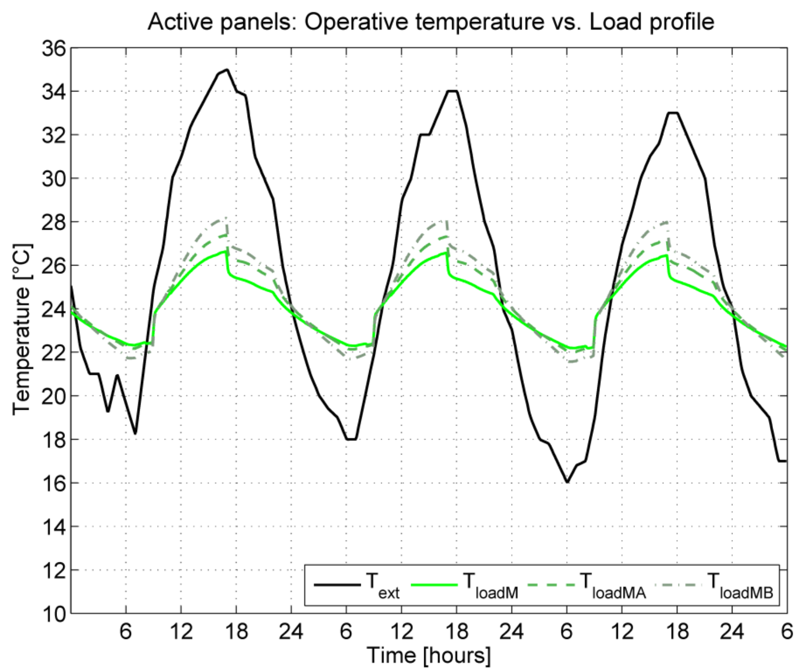


Figure 7-29: Active panels – operative temperature vs. cooling load profile

The results for office operative temperature, under the different cooling load profiles, are shown in Figure 7-29. For profile ‘load M’, the resulted daily operative temperature variation was 22.2-26.4°C (4.2K), for profile 'load MA' it was 22.2-27.2°C (5K), and for profile 'load MB' 21.9-28.1°C (6.2K). The active ceiling panels could limit the peak of indoor operative temperature to the upper limit for thermal comfort of 27°C, for cooling load profile 'load M' and for 'load MA' the resulted peak temperature was just 0.2K above the limit. However, for profile 'load MB', indoor operative temperatures up to 28.1°C were encountered.

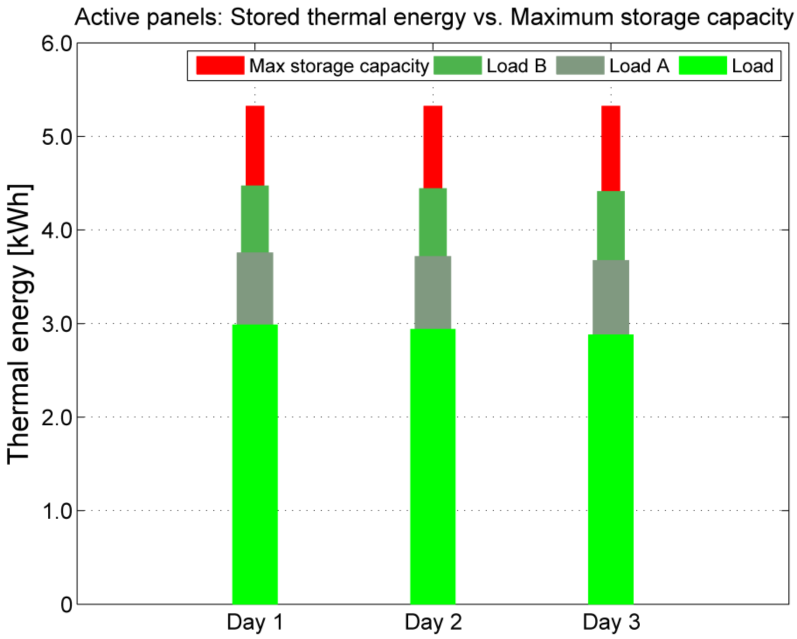


Figure 7-30: Active panels – stored thermal energy vs. cooling load profile

The stored thermal energy in the active ceiling panels, under the studied cooling load profiles is given in Figure 7-30. For profile 'load M', the stored thermal energy during the hours of occupancy was 132 Wh/m^2, which is about 49% of the daily cooling load of 268 Wh/m^2, for profile 'load MA' it was 163 Wh/m^2 corresponding to 51% of the daily cooling load of 318 Wh/m^2, and for profile 'load MB' 198 Wh/m^2 were stored in the ceiling panels being about 52% of the daily cooling load of 379 Wh/m^2.

7.8.3 Passive vs. Active ceiling panels – temperature control and thermal mass utilization comparison

An interesting moment would be to compare the performance of passive ceiling panels with night-time ventilation with the one of active-ceiling panels with night cooling through the embedded pipes system. Since the cooling load and internal heat gain profiles for "load CB" and "load MA" (307 Wh/m^2 vs. 318 Wh/m^2 cooling load, 44 W/m^2 vs. 45 W/m^2 peak internal sensible heat gain), as well as for "load CA" and "load MB" (386 Wh/m^2 vs. 379 Wh/m^2 cooling load, 57 W/m^2 vs. 55 W/m^2 peak internal sensible heat gain) are quite similar, Figure 7-31, a direct comparison between these case studies was possible. What could be noticed as a main distinction between the two climatic zones is the peak space sensible heat gain for Copenhagen was occurring at around 12:30 p.m., 1 hour earlier than for the location of Madrid occurring at 1:30 p.m. Those results were due to the time difference of occurrence of the peak solar heat gain at the two locations, due to their different latitude.

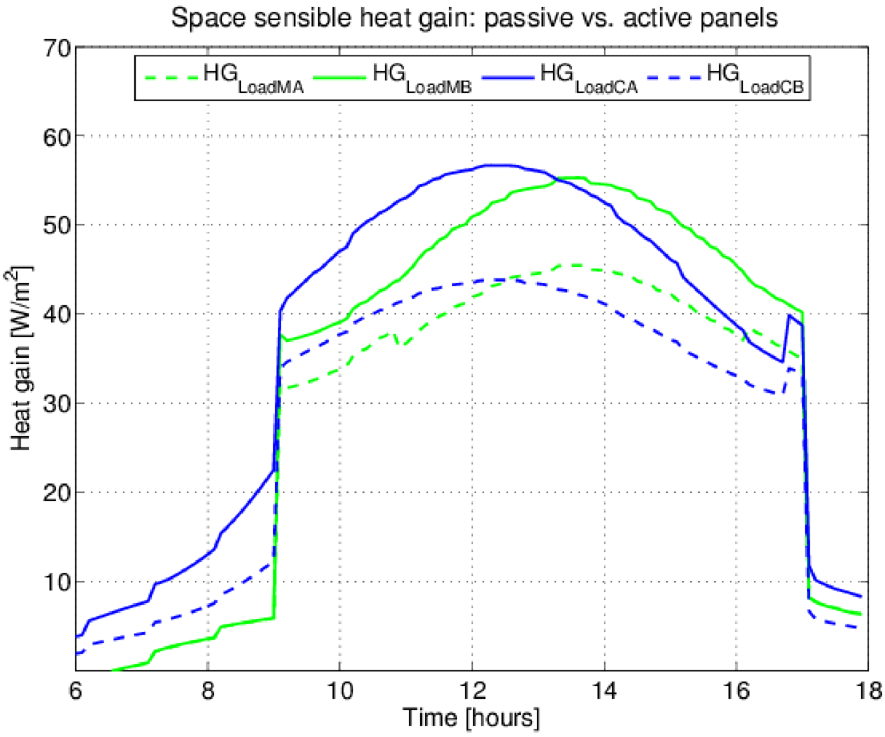


Figure 7-31: Space sensible heat gains for case studies 'load CA', 'load CB', 'load MA' and 'load MB'

Before analyzing the behavior of the office spaces with passive and active PCM-gypsum ceiling panels, some of the thermal properties influencing the thermal performance of the ceiling panels are discussed. For a typical internal thermal mass "structure" like the PCM-gypsum ceiling panels, the basic heat transfer processes can be described by conduction, convection, and radiation. There is a convective heat transfer process at the surface of the ceiling panels and a radiant heat transfer between them and other surfaces. The radiant heat transfer was considered constant during the simulations. The convective heat transfer coefficient depends on the temperature difference between panels' surface and the indoor air, and the direction of heat flow. It the present simulation models, the convective heat transfer at the ceiling panels' surface was defined as depending only on the temperature difference between panels' surface and indoor air by the following mathematical formula:

$$\alpha_{conv} = 2 * \left(T_{panels\,surface} - T_{airsurface}\right)^{0.31} \ \frac{W}{m^2K} \quad (7.1)$$

The conduction heat transfer takes place in the interior of the panels and depends on several properties. For storing heat in the PCM-gypsum ceiling panels, important thermal properties considered were the heat capacity by volume and the heat-absorption rate. The first property determined the ability of the ceiling panels to store thermal energy and since the passive and active ceiling panels were built of the same PCM-gypsum material, they exhibited identical volumetric heat capacity. The heat-absorption rate determines the ability of these ceiling panels to absorb thermal energy, and could be quantified by the thermal diffusivity of the PCM-gypsum composite. Here is where the conductivity and specific heat capacity come into role (see Eq. 7.1). According to the relation given by Eq. 7.1, increase of the thermal conductivity will contribute towards increase of the heat-absorption rate, while increase of the heat capacity will decrease that rate. When the PCM temperature is within the fusion temperature range, the ceiling panels have highest heat storage capacity, but lowest heat-absorption rate, which decreases the rate of storage of the space sensible heat gains in the ceiling panels.

In Figure 7-32 andFigure **7-33** are shown the indoor operative temperatures, the cumulated space sensible heat gains and the cumulated stored thermal energy in the ceiling panels for a single day, for load profiles 'load CB' & 'load MA' and load profiles 'load CA' & 'load MB'. The graphs show the parameters variation within the time frame 6 a.m. – 6 p.m. (from discontinuing the night-time cooling until one hour after daily occupancy period).

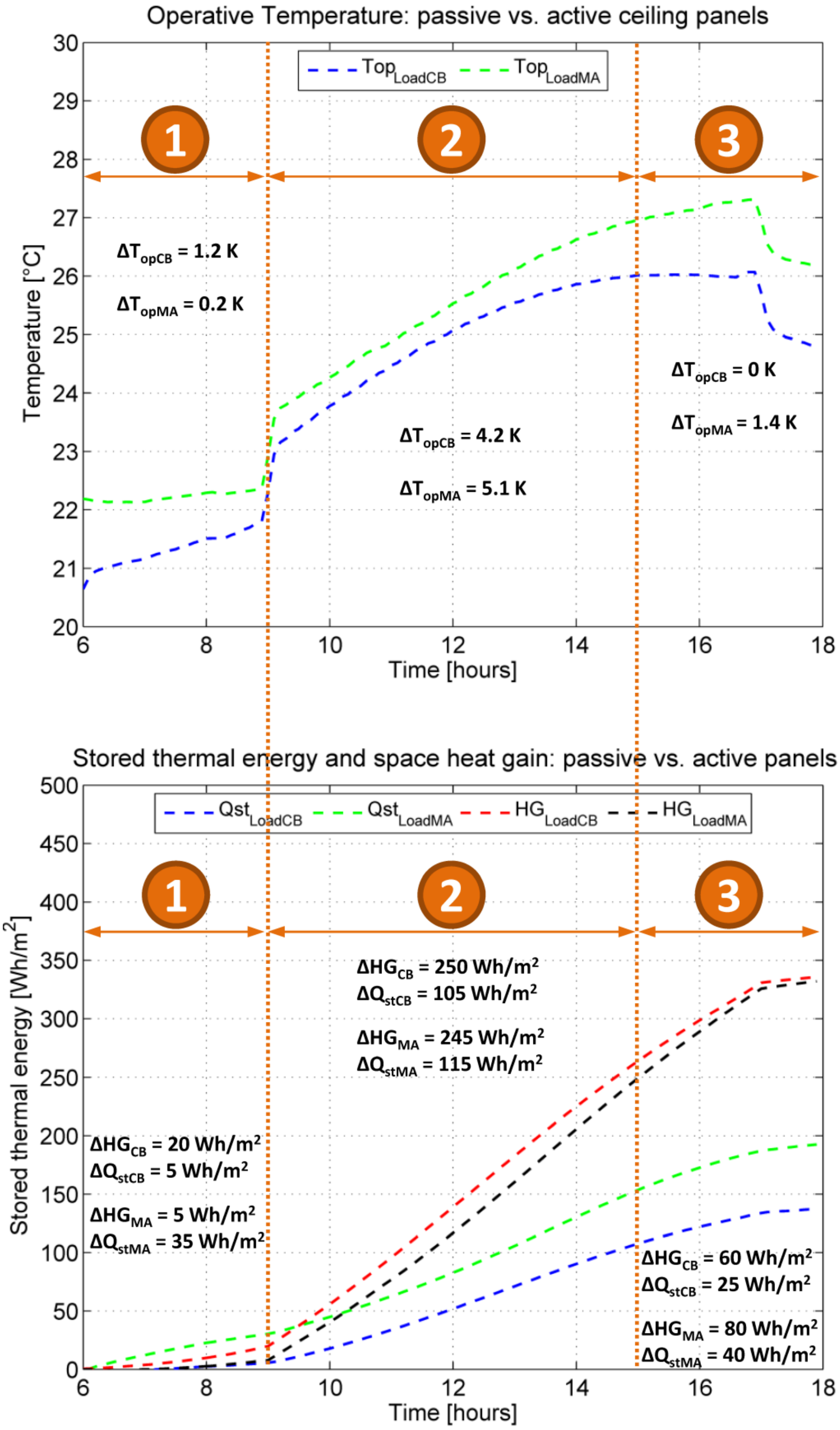


Figure 7-32: Operative temperatures and cumulated space sensible heat gains and stored thermal energy for case studies 'load CB' (passive) and 'load MA' (active)

That time period is divided in three sub periods:

- (1) 6 a.m. – 9 a.m.: from discontinuing night-time cooling operation until hours of occupancy
- (2) 9 a.m. – 3 p.m.: from morning occupancy hours to mid-afternoon
- (3) 3 p.m. – 6 p.m.: from mid-afternoon until 1 hour after end of occupancy period

The thermal performance of the PCM-gypsum ceiling panels in each of the sub-periods is considered, due to different phenomenon occurring in each time interval.

For time period (1), comparing the simulation models with identical space sensible heat gains (‘load CB’ vs. ‘load MA’, and ‘load CB’ vs. ‘load MA’), it was observed that although the different night-time cooling resulted in the same temperature 21°C of the PCM ceiling panels (to ensure discharging of the stored thermal energy from the previous day), there was different effect on the office operative temperature. For the office models with passive ceiling panels, ‘load CA’ and ‘load CB’, due to the ventilative cooling the indoor operative temperature was brought down to 20.5°C and 20.6°C at 6 a.m. For the models with active ceiling panels, ‘load MA’ and ‘load MB’, due to the local cooling by the embedded pipes system, there has been less effect on the indoor operative temperature, resulting in 22.2°C and 21.8°C at 6 a.m. The resultant difference in operative temperatures (1.6K between ‘load CB’ & ‘load MA’; 1.3K between ‘load CA’ & ‘load MB’) in the early morning hours had a significant effect on the difference in performance between the passive and active ceiling panels, due to the difference in the resultant combined heat transfer coefficient at the surface of the ceiling panels, and respectively the different heat-absorption rate.

For starting office temperature of 22.2°C and 21.8°C at 6 a.m.(simulation models ’load MA’ and ’load MB’), the PCM in the active ceiling panels begins to melt and absorb space heat gains already at early morning before occupancy hours. The passive ceiling panels simulation models, ‘load CA’ and ‘load CB’, had indoor temperatures lower or just reaching the PCM melting temperature range at 6 a.m. (20.5°C and 20.6°C respectively), and the stored thermal energy in the ceiling panels prior to the hours of occupancy is very limited. However, due to some space sensible heat gains present, there is an increase of the office temperature to 21.8°C (‘load CB’) and 22.2°C (‘load CA’) for the models with passive panels. The stored latent heat, just prior to the hours of occupancy, has been 35 Wh/m^2 for ‘load MA’ and ‘load MB’ office models with active ceiling panels, compared to 5 Wh/m^2 for ‘load CB’ and 10 Wh/m^2 for ‘load CA’ office models with passive panels, Figure 7-32.

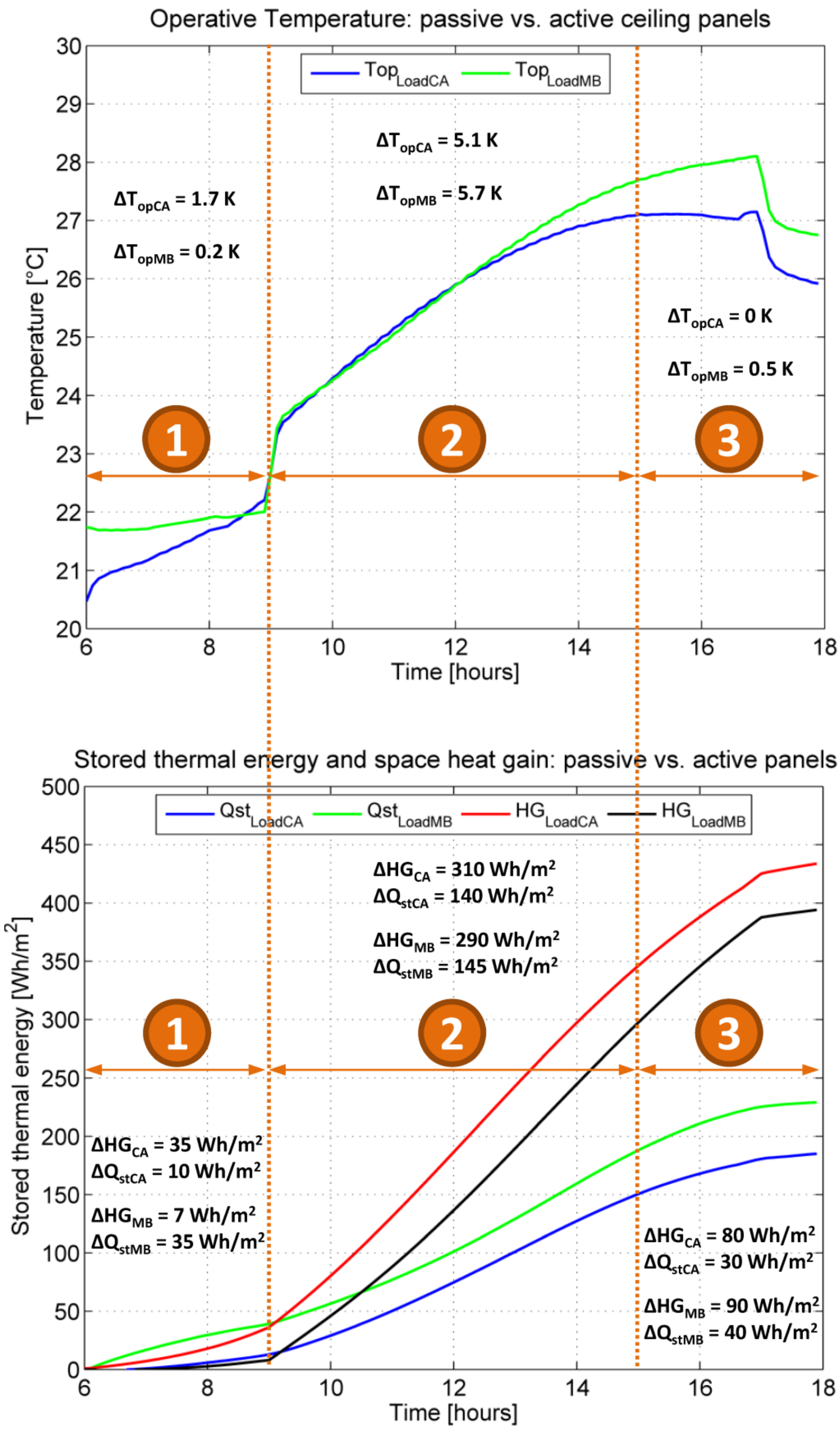


Figure 7-33: Operative temperatures and cumulated space sensible heat gains and stored thermal energy for case studies 'load CA' (passive) and 'load MB' (active)

Considering the space sensible heat gains and rate of storage of thermal energy in the ceiling panels during time period (2), shown in Figure 7-32 and Figure 7-33, it can be seen that there is an amplitude difference between the cumulated stored thermal energy and the cumulated space heat gains. These amplitude differences were attributed to the PCM-gypsum panels' temperature dependent heat-absorption capacity. As already discussed, the heat-absorption rate of the ceiling panels can be quantified by the temperature dependent thermal diffusivity of the PCM-gypsum composite. The difference between the space heat gains and the heat-absorption rate by the ceiling panels results in increase of the indoor operative temperature. For time period (2), the rates of indoor operative temperature increase and the storage rate of thermal energy have been identical for the office models, with passive and active ceiling panels, with identical space sensible heat gains ('load CB' vs. 'load MA', and , 'load CA' vs 'load MB').

As already discussed, the heat storage capacity or heat-absorption rate of the ceiling panels is a function of the temperature dependent heat storage capacity and thermal effusivity of the PCM-gypsum composite material. It will depend on the temperature distribution within the panels' thickness. When thermal energy is stored in the ceiling panels, their temperature increases from the surface layer facing the indoor space towards the panels' interior, and when the temperature in the ceiling panels rises above the PCM melting temperature range, the heat storage capacity will start to decrease from their surface layers facing the room air towards the interior of the panels and the upper surface layers facing the ceiling. That phenomenon would continue until the whole latent heat storage of the ceiling panels is utilized.

The decrease in time of the heat storage capacity of the surface layers (facing the office space) of the ceiling panels would result in a decrease of the heat storage rate in the ceiling panels. When the high storage capacity layers are not in direct contact with the indoor air but they are located deeper in the panels, heat is not directly absorbed by the PCM but it should be transferred first towards the interior of the panels.

Considering the above discussed phenomenon in time period (3), the combined effect of decreased heat storage rate in the PCM-gypsum ceiling panels in time (due to complete utilization of the PCM material in the surface layers of the ceiling panels) and the fact that the peak of sensible heat gains for the location of Madrid occurs at a later time in the afternoon (compared to the location of Copenhagen), can be seen in Figure 7-32. For the passive ceiling panels models 'load CA' and 'load CB', the added by the PCM-gypsum panels thermal mass manages to flatten the indoor operative temperature variation to about 27°C and 26°C respectively in the late afternoon hours from 3 p.m. to 5 p.m., while for the active panels model 'load MA' and 'load MB', the operative temperature variation is less dampened, due to the decreased heat-absorption rate, and keeps rising to 27.2°C and 28.1°C respectively.

The last point to consider in the ceiling panels' thermal performance evaluation is to determine the effect of cooling load intensity (space sensible heat gains intensity). For that evaluation the average (during occupancy hours) rate of internal heat gains, average rate of heat-absorption by the ceiling panels, and average rate of increase of the internal operative temperature are used. The comparison here is made between the simulation models with passive panels ‘load CA’ vs. ‘load CB’, and the simulation models with active panels ‘load MA’ vs. ‘load MB’. The results are presented in Table 7-6.

Table 7-6: PCM-gypsum ceiling panels thermal performance vs. space sensible heat gain intensity

Building model	‘load CA’	‘load CB’	‘load MA’	‘load MB’
HG rate [Wh/m^2h]	49	40	39	48
Q_{st} rate [Wh/m^2h]	22	18	17	25
T_{op} increase rate [K/h]	0.64	0.53	0.64	0.71

The presented in Table 7-6 results suggested that increase in the cooling load intensity (higher space sensible heat gain rate) results in increased rate of heat storage in the ceiling panels. However, there is negative effect on the rate of increase of indoor operative temperature, which increases with increase of the internal thermal loads. Additionally, comparing the internal operative temperature variation between the different simulation models, it can be seen that the higher internal loads resulted in 1.1K increase of the indoor operative temperature for the simulation models with passive ceiling panels and 0.9K increase of the maximum operative temperature for the simulation models with active ceiling panels.

7.8.4 Passive vs. Active ceiling panels – cooling load management and energy savings potential

In the previous parts of this chapter, the thermal performance of the PCM-gypsum ceiling panels in terms of temperature control and storage capacity utilization was evaluated under different boundary conditions. In the present section, further analysis on the thermal performance of passive and active PCM-gypsum ceiling panels, in terms of cooling load peak reduction and the shifting of the daily cooling demand to night-time hours, is given.

For the present analysis, two of the previously used simulation models were selected due to the fact that the indoor operative temperature in these models resulted within the comfort limits of 22-27°C during the hours of occupancy, namely a simulation model with passive ceiling panels and a load profile ‘load CB’, and a model with active ceiling panels and a load profile ‘load MA’. These two simulation models have similar space sensible heat gains, and were used to show the potential benefits and differences between the passive ventilative cooling by night-time natural ventilation and the embedded pipes night-time cooling.

In Table 7-7 is given energy balance data for the office space for a typical summer day (24h period). The internal, infiltration, solar radiation and transmission heat gains are given under a common parameter, the space sensible heat gain. When a '-' sign is used in the table, it means that the given thermal gain is extracted heat from the space or heat stored in the PCM-gypsum panels.

The use of passive ceiling panels combined with night-time natural ventilation was assessed for the moderate summer climate of Copenhagen, Denmark, by the simulation model 'load CB'. The thermal loads of the office space and HVAC plant are shown in Figure 7-34. Using passive cooling by natural night-time ventilation allowed reduction of the energy consumption for cooling by the utilizing the free cooling potential of the cold ambient air at night. The energy used for cooling was reduced by 69% (100 Wh/m^2 of the cooling demand covered by daytime ventilation, 238 Wh/m^2 provided by free night-time cooling by natural ventilation). Additionally, by storing the excess heat gains during daytime in the PCM-gypsum ceiling panels reduced the peak cooling loads by 70% (from 1 kW to 0.3 kW). In that way the cooling system did not have to be designed to cover the maximum thermal load and allowed to reduce the capacity of the refrigeration equipment providing further economies.

Table 7-7: Energy balance for the office space for a typical summer day (24h period)

Building model	**'load MA'**	**'load CB'**
Ventilation daytime [Wh/m^2]	**-112**	**-100**
Ventilation night-time [Wh/m^2]	n/a	**-238**
Space sensible heat gains [Wh/m^2]	**336**	**338**
Cooling water side (embedded pipes system) [Wh/m^2]	**-224**	n/a
Thermal energy stored in the ceiling panels [Wh/m^2]	***188***	***142***

Comparing the thermal energy stored in the PCM-gypsum ceiling panels (142 Wh/m^2) and the space cooling load shifted to night-time (238 Wh/m^2), it can be seen a certain mismatch between these numbers. About 60% of the space sensible heat gains were stored in the PCM ceiling panels. The excess heat gains during daytime amounted to 40% (76 Wh/m^2), and were causing the office operative temperature rise of 5.4K from 20.6°C (6 a.m.) to 26°C (5 p.m.).

The use of active ceiling panels with embedded pipes for night-time cooling were considered for the hot summer climate of Madrid, Spain, in the simulation model 'load MA'. The thermal loads of the office space and HVAC plant are given in Figure 7-35.

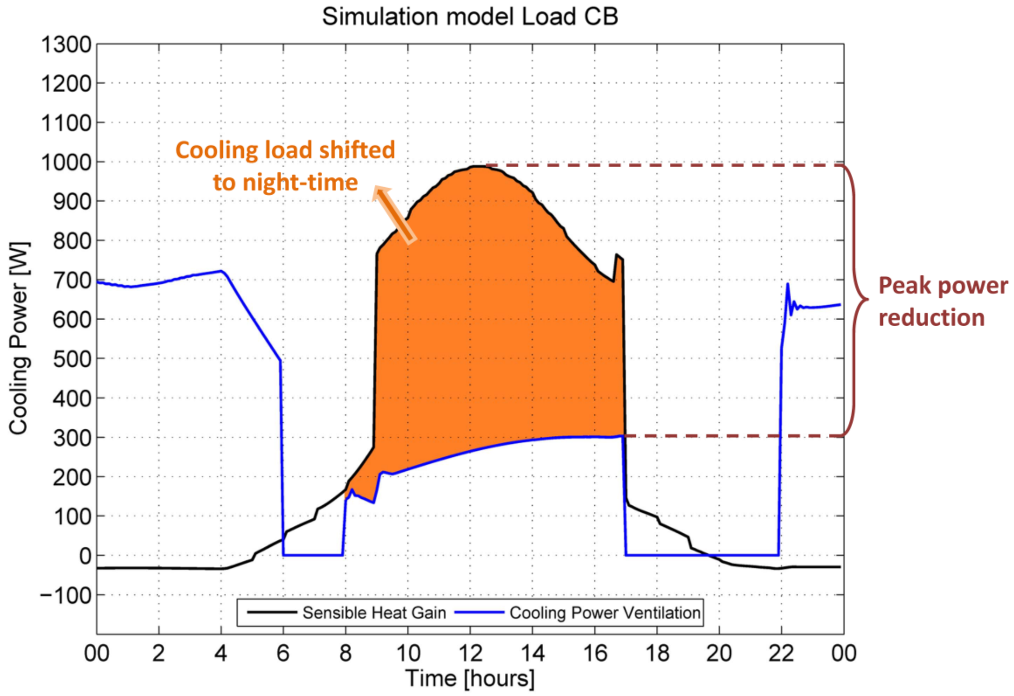


Figure 7-34: Load shifting and peak shaving effects in office with passive PCM-gypsum ceiling panels ('load CB')

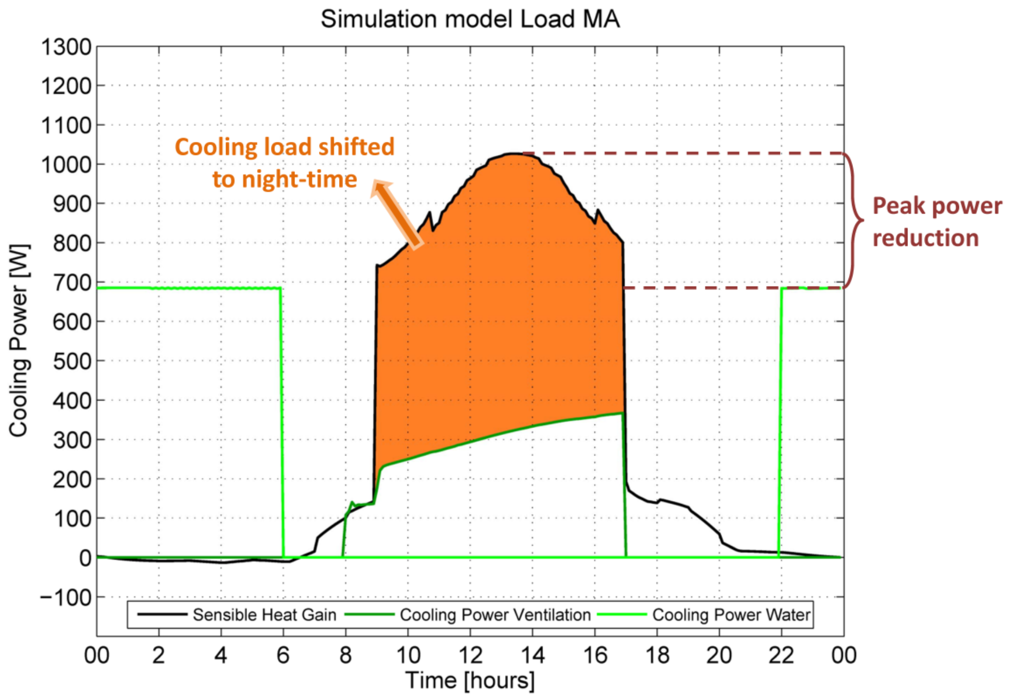


Figure 7-35: Load shifting and peak shaving effects in office with active PCM-gypsum ceiling panels ('load MA')

A difference in comparison with the passive ceiling panels system is that here the active system did not provide energy savings through the use of passive cooling techniques. However, the concept provided other benefits. Due to the active utilization of the thermal mass added by the PCM-gypsum ceiling panels, cooling loads could be reduced and shifted to off-peak hours independently of the local climatic conditions (system efficiency dos not depend on the availability of cold ambient air). There was no need to instantly supply the cooling demand of the space to the ceiling panels. Instead it can was transferred with a time shift and at power levels which differed from the actual demand. The peak power reduction in terms of HVAC system sizing was reduced by 32% (1.02 kW peak cooling demand during daytime vs. 0.69 kW peak cooling demand by the embedded pipes system at night-time). Additionally, the peak power reduction during occupancy hours was reduced by 64% (1.02 kW peak cooling demand during daytime vs. 0.37 kW peak cooling demand covered by daytime ventilation).

In terms of thermal loads management, 224 Wh/m^2 were shifted (for night-time cooling by the embedded pipes system), which was 67% of the total cooling load of 336 Wh/m^2. Shifting of the daily cooling loads to night-time benefits from operation at a reduced night-time electricity price, and the concept could benefit from time-of-use electricity tariffs.

Comparing the thermal energy stored in the PCM-gypsum ceiling panels (188 Wh/m^2) and the space cooling load shifted to night-time (224 Wh/m^2), it can be seen that about 84% of the space sensible heat gains were stored in the PCM ceiling panels. The excess heat gains during daytime, of 16% (36 Wh/m^2), were causing the office operative temperature rise of 5K from 22.2°C (6 a.m.) to 27.2°C (5 p.m.).

7.9 Summary

A summary now outlines the most important findings and results from the parametric study.

7.9.1 Effect of PCM fusion temperature

Three PCM materials with different fusion temperatures were investigated, their thermal properties given in Table 7-2. Depending on the PCM melting temperature range, different daily operative temperatures were achieved in the simulation case studies. For the active PCM-gypsum ceiling panels, due to the local heat extraction from the panels by the embedded pipes system, the indoor operative temperature range was directly dependent on the PCM melting temperature: the lower this temperature, the lower the operative temperature indoors, Figure 7-10. For ceiling panels with PCM21 the indoor operative temperature varied between 21-25.2°C during the hours of occupancy, and when PCM with a higher melting temperature was used in the panels, the operative temperatures indoors varied in the range 22-26.3°C (for PCM23) and 24-28.3°C (for PCM26).

Different results were obtained in the case of night-time ventilative cooling and passive ceiling panels, Figure 7-5. For the ceiling panels with PCM23 the indoor operative temperature varied between 21°C and 27°C during the hours of occupancy, while for panels with PCM26, higher operative temperatures occurred (23-29°C). Using PCM with lower melting temperature (PCM21), did not result in lowering the office operative temperature (21-28°C). This was attributed to the fact that the night-time ventilative cooling was limited to office temperatures of 21°C due to comfort considerations, which prevented the complete solidification of the PCM21 material in the ceiling panels and respectively resulted in a limited storage capacity available on the following day. Unless the thermal comfort limits on night-time ventilative cooling are made more loose, using PCMs with somehow lower melting temperature (as in the case of PCM21), will not be an efficient solution.

Considering the utilization of the added by the PCM-gypsum ceiling panels thermal mass, when the night-time embedded pipes cooling principle was used the ceiling panels with PCM21 showed the highest storage capacity utilization (154 Wh/m^2 vs. 137 Wh/m^2 and 106 Wh/m^2 for PCM23 and PCM26 respectively), Figure 7-14. However due to temperature control considerations and concerns about use of excess energy for night time cooling due to the needed for lower temperature of the cooling medium used in the embedded pipes system compared to ceiling panels with PCM23, the high thermal mass utilization benefit might be outplaced by the insufficient thermal comfort.

For the passive ceiling panels concept with night-time cooling by natural ventilation the highest amount of stored thermal energy was achieved for panels with PCM23 (159 Wh/m^2 vs. 123 Wh/m^2 and 110 Wh/m^2 for PCM 26 and PCM 21 respectively). For panels with PCM21, due to the insufficient cooling provided by the natural night-time ventilation (thermal comfort restrictions) and the resultant not completely discharged storage capacity of the ceiling panels, they showed the lowest storage capacity utilization on the following day regardless of their lowest fusion temperature.

Summarizing the simulation results, it can be concluded that PCM23 material with fusion temperature of 23°C and melting range 21-25°C would be most suitable solution for use in the PCM-gypsum ceiling panels, in terms of temperature control and thermal mass utilization, for both the passive and active concepts.

7.9.2 Effect of PCM-gypsum thermal conductivity

PCM-gypsum boards with a higher thermal conductivity are expected to perform better, due to the higher heat-absorption rates during melting of the PCM material in the ceiling panels. The effect of three different thermal conductivities of the PCM-gypsum composite material were investigated: reference (0.384 W/mK), half (0.19 W/mK) and double (0.76 W/mK) of the reference. Ceiling panels with PCM23 were used for the thermal conductivity evaluation.

Increasing the PCM-gypsum thermal conductivity from 0.19 → 0.384 → 0.76 W/mK resulted in decrease of the peak indoor operative temperature from 27.4 → 27 → 26.8°C, for the passive ceiling panels simulation models, Figure 7-15. Similar behaviour was observed for the simulation models with active ceiling panels, where increasing the PCM-gypsum thermal conductivity from 0.19 → 0.384 → 0.76 W/mK resulted in decrease of the peak indoor operative temperature from 26.7 → 26.4 → 26.2°C.

The amount of stored thermal energy for the passive panels models are shown in Figure 34. In relative values, increase of the PCM-gypsum thermal conductivity from 0.19 → 0.384 → 0.76, resulted in maximum increase of the stored thermal energy by 6% and 9%, Figure 7-19. The amount of stored thermal energy for the passive panels models, shown in Figure 7-24, reveal that increase of the PCM-gypsum thermal conductivity from 0.19 → 0.384 → 0.76 resulted in maximum increase of the stored thermal energy by 3% and 6%.

The results from the simulation study on the effect of PCM-gypsum thermal conductivity on the active ceiling panels' thermal performance, show minor benefits for the studied conductivity range. A tendency for slight increase of the benefit of higher thermal conductivity for space cooling loads with higher intensity could be expected, which can be noticed if the benefits seen in the case studies with passive ceiling panels are compared to the ones with active ceiling panels (maximum space sensible heat gains for the cases with active panels of 37 W/m^2 vs. 50 W/m^2 for the cases with passive panels).

7.9.3 Passive vs. active ceiling panels: cooling load daily profile, cooling load management and energy saving potential

The performance of passive ceiling panels with night-time ventilation was compared with the one of active-ceiling panels with night cooling through the embedded pipes system for identical space sensible heat gains, Figure 46.

The obtained results, shown in Table 7-6 and Figure 7-32 & Figure **7-33**, suggested that increase in the cooling load intensity results in increased rate of heat storage in the ceiling panels. However, there was negative effect on the rate of increase of indoor operative temperature, which increases with increase of the internal thermal loads. A comparison between the internal operative temperature variation in the different simulation models showed that higher internal loads resulted in 1.1K (307 Wh/m^2 vs. 386 Wh/m^2) increase of the indoor operative temperature for the simulation models with passive ceiling panels and 0.9K (318 Wh/m^2 vs. 379 Wh/m^2) increase of the maximum operative temperature for the simulation models with active ceiling panels.

In terms of cooling load management, for the passive ceiling panels combined with night-time natural ventilation the energy used for cooling was reduced by 69% resulted in direct energy savings. Additionally, the peak cooling load was reduced by 70% which resulted in direct reduction of the maximum power capacity of the HVAC system.

The active ceiling panels concept did not provide direct energy savings through use of passive cooling techniques. However, the concept provided other benefits. The peak power reduction in terms of needed total HVAC system capacity was 32%. Additionally, the peak power reduction during occupancy hours was reduced by 64%. About 67% of the total daily cooling load was shifted to night-time hours, which was beneficial in terms of system operation at a reduced night-time electricity price cost savings through time-of-use electricity tariffs.

PART IV: EXPERIMENTAL STUDY

Part IV are presented a series of experimental case studies in which the performance of ceiling panels with PCM is evaluated, in terms of temperature control and cooling load management, for a simulated office environment in a climate chamber. Additionally, the experimental results are compared with results from a computer simulation model of the experimental chambe, in order to evaluate of the accuracy of a predicted through computer simulations behavior.

8. Laboratory Experimental Investigation of Ceiling Panels with Phase Change Material for Building Thermal Mass Enhancement and Peak Load Management in Office Buildings

The main objectives of the experimental study were to evaluate the performance, in terms of temperature control and cooling load management, of ceiling panels with PCM for a typical office environment. The incorporation of PCM in the chilled ceiling panels has the purpose of adding thermal mass to the “building” construction which was utilized for decreasing the peak cooling load and shifting of the space cooling needs to night-time hours.

The experimental study was carried out in a climatic Chamber 6 of the International Centre for Indoor Environment and Energy (ICIEE), at the Department of Civil Engineering of the Technical University of Denmark. Following the objectives an experimental set-up was arranged in the climatic chamber as a typical office space. The PCM panels’ system thermal performance was evaluated, through a series of experimental case studies, for different control strategies and operation principles, including:

- Active (night-time embedded pipes system) vs. passive (night ventilation) discharge
- Internal loads intensity and cooling load pattern

At the end of the Chapter, the results from the experimental study are compared with the results from a computer simulation model, build in TRNSYS 17, in order to evaluate of the accuracy the predicted behavior of PCM ceiling panels through computer simulations.

8.1 PCM-clay ceiling panels description and thermal properties

The ceiling panels with PCM used in the experimental study were built of micro-encapsulated paraffin material incorporated in a 25 mm thick clayboard with dimensions 125 cm x 62.5 cm. For structural support, there was a cardboard inserted as a middle layer of the ceiling panel. The micro-encapsulated paraffin used was BASF Micronal® PCM type DS 5040X with a melting temperature of 23°C (Jahns 1999). Data on the thermal properties of the PCM, clay and cardboard materials are given in Table 8-1.

Table 8-1: Thermal properties of microencapsulated PCM, Clay and cardboard (Source: BASF)

Material	DS 5040X	Cardboard	Clay
Melting range [°C]	21-25	-	-
Fusion temp. [°C]	23	-	-
Specific latent heat [kJ/kg]	110	-	-
Specific heat capacity [kJ/kgK]	-	2.1	1.0
Density [kg/m^3]	980	270	1300
Thermal conductivity [W/mK]	0.14	0.055	0.47

The total amount of micro-encapsulated PCM used in a panel was 6 kg, which corresponds to about 26% PCM by weight. Additionally, regularly arranged Alu-PEX pipes (8 mm ext. diameter, 10 cm spacing) were embedded in the PCM-clayboard, to be used for active discharging of the stored thermal energy during night-time. The pipes were embedded on one side of the cardboard plate. During installation, the side with embedded pipes was facing the ceiling of the experimental chamber, and the side without embedded pipes was facing the office space. The structure of the panel is shown in Figure 8-1.

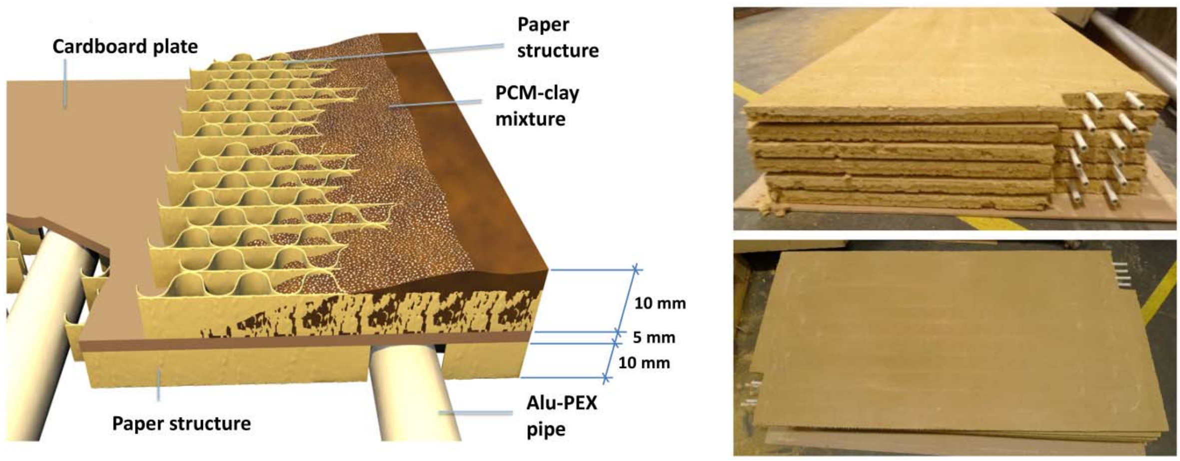


Figure 8-1: PCM-clayboard panels (upwards facing the room)

Due to the incorporation of the micro-encapsulated PCM in the clayboard, data on the thermal properties of the composite clayboard panel was needed. Two approaches were taken to determine the thermal conductivity and specific heat capacity as a function of temperature for the PCM-clayboard ceiling panels, a theoretical and an experimental ones.

The theoretical thermal conductivity of the ceiling panels was determined using the approach for average thermal conductivity for series and parallel multiphase materials, given by Wong et al. (2007). First, the average thermal conductivity of the PCM-clay mixture was approximated as a series multiphase material, by Equation 8.1. Thereafter the average thermal conductivity of the PCM-clayboard was approximated as a parallel multiphase material, with layers PCM-clay→cardboard→PCM-clay, by Equation 8.2. In Equations 8.1 and 8.2, φ_i stands for the volume fraction of a particular component material and λ_i is the thermal conductivity.

$$\lambda_{PCM-clay} = \lambda_{PCM} \cdot \varphi_{PCM} + \lambda_{clay} \cdot \varphi_{clay} \quad \left[\frac{W}{mK}\right] \qquad (8.1)$$

$$\lambda_{PCM-clayboard} = \frac{\lambda_{PCM-clay} \cdot \lambda_{cardboard} \cdot \lambda_{PCM-clay}}{2 \cdot \varphi_{PCM-clay} \cdot \lambda_{PCM-clay} \cdot \lambda_{cardboard} + \varphi_{cardboard} \cdot \lambda_{PCM-clay} \cdot \lambda_{PCM-clay}} \quad \left[\frac{W}{mK}\right] \qquad (8.2)$$

The theoretical method for specific heat capacity determination of the PCM-clayboard utilizes the weight average Equation 8.3 for clay and PCM, where the micro-encapsulated PCM specific heat capacity is obtained through DSC measurements (BASF personal communication). In Equation 8.3, $\%_i$ is the weight fraction of a particular component material and Cp_i is the specific heat capacity.

$$Cp_{PCM-clayboard} = Cp_{PCM} \cdot "\%_{PCM}" + Cp_{clay} \cdot (1 - "\%_{\mathrm{PCM}}") \quad \left[\frac{kJ}{kg}\right] \qquad (8.3)$$

An experimental facility, located at the Department of Civil Engineering at Aalborg University (Denmark), was used to determine the thermal conductivity and specific heat capacity as a function of temperature for the PCM-clayboard panels. The methods and equipment for determination of thermal conductivity and specific heat capacity as function of temperature of building materials with incorporated micro-encapsulated PCM, using a guarded hot plate apparatus, described in Pomianowski et al. (2011) and Pomianowski et al. (2012), were used to determine the thermal properties of the PCM-clayboard. A specimen with dimensions 15 x 15 cm was cut from a PCM-clayboard panel and used in the thermal properties determination tests.

Table 8-2: Average thermal conductivity comparison for PCM-clayboard

Method	Thermal conductivity [W/mK]
Theoretical	0.155
Experimental	0.153

In Table 8-2 are shown the theoretically and experimentally determined thermal conductivities, while in Figure 8-2 is shown a comparison between the experimental and theoretical specific heat capacities as a function of temperature, for the PCM-clayboard ceiling panels. The results for PCM-clayboard thermal conductivity suggests that the theoretical approach could give a very good estimation for the ceiling panels under investigation here. A difference of 1.3% was encountered between the measured and calculated thermal conductivity.

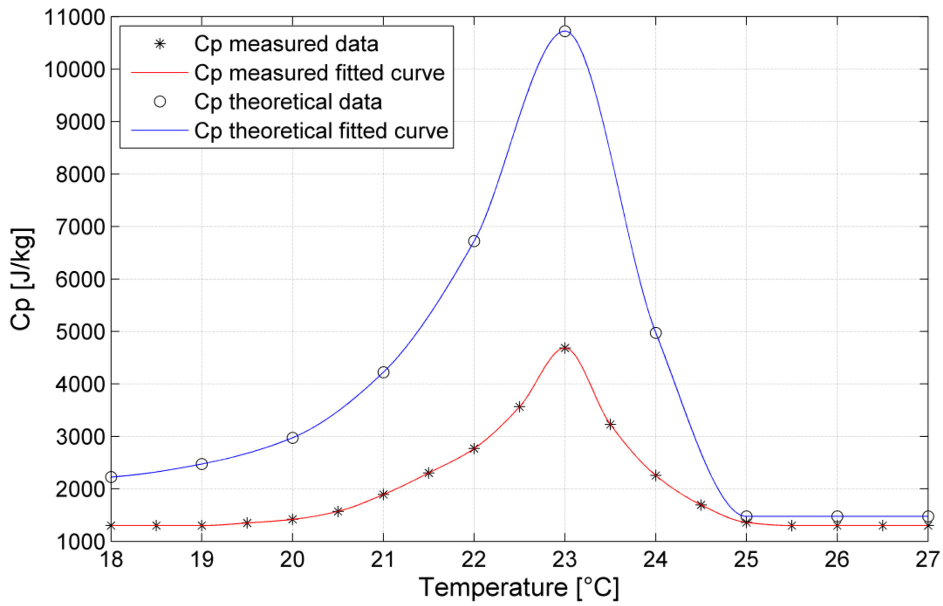


Figure 8-2: Measured vs. theoretical specific heat capacity of PCM-clayboard

The results for specific heat capacity as a function of temperature of the PCM-clayboard panels, Figure 8-2, show big difference between the measured and theoretical results. The theoretical method that uses the weight-average method given by Equation 8.3 results in more than twice higher heat capacity values compared to the results based on the measurements. The measured lower specific heat capacity is most probably due to rupture of some of the PCM microcapsules during clayboard production. The obtained results somehow repeat the results obtained by Pomianowski et al. (2012), where the authors determined the specific heat capacity of micro-encapsulated PCM mixed with concrete at different ratios, both theoretically and through measurements. In that work it was shown similar discrepancy between the theoretical and measured specific heat capacities, although for lower PCM content by weight (1-6% compared to 26% in the present study).

8.2 Experimental set-up

Experimental set-up was built in a climatic chamber, arranged as a typical office space and equipped with different heat gain simulators to represent occupants, equipment and solar heat gains. The chamber had ventilation system and chilled water system capable of providing cold water at different temperatures and flow rate. In addition, measurement equipment was installed to monitor different parameters of the HVAC system, the thermal environment and heat gains intensity in the space, as well as surface temperatures and heat flux of the PCM-clayboard ceiling panels. The measurement equipment and part of the control of the chamber was done by a common control/data logging system built for the purpose of the experiment. External systems were the ventilation system, which was the main ventilation system of ICIEE Laboratory, and the Chiller (refrigeration equipment) providing cold water for cooling the suspended ceiling panels.

8.2.1 Climate chamber

The climate chamber where the experiment was conducted is in the interior of a bigger building, so it is not affected directly by outdoor weather conditions. The chamber has dimensions of 5.4 x 4.2 x 2.5 m, resulting in a total floor area of 22.7 m^2 and a volume of 56.7 m^3. The height of the chamber is measured from the floor up to the suspended ceiling with PCM-clayboard panels. Additionally, there are 0.5 m from the suspended ceiling to the roof of the chamber, forming a plenum with a volume of 11.35 m^3 where the ventilation air is supplied. Schematic view is shown in Figure 8-3, while in Figure 8-4 is shown a photo of the experimental set-up.

The envelope of the climate chamber is built of internal and external steel sheets separated by 10 cm of insulation in the walls, roof and floor. This construction has a very low thermal mass, resulting in a very lightweight envelope. An average heat loss coefficient through the chamber envelope of 30.1 W/K was estimated.

8.2.2 Heat gains and solar radiation simulator

In terms of heat gains variation, the internal heat gains were the same in all investigated experimental case studies. In Table 8-3 are given the internal heat gains from occupants, equipment and lighting. These internal loads were continuously present in the experimental office space during simulated hours of occupancy (9 a.m. – 5 p.m.).

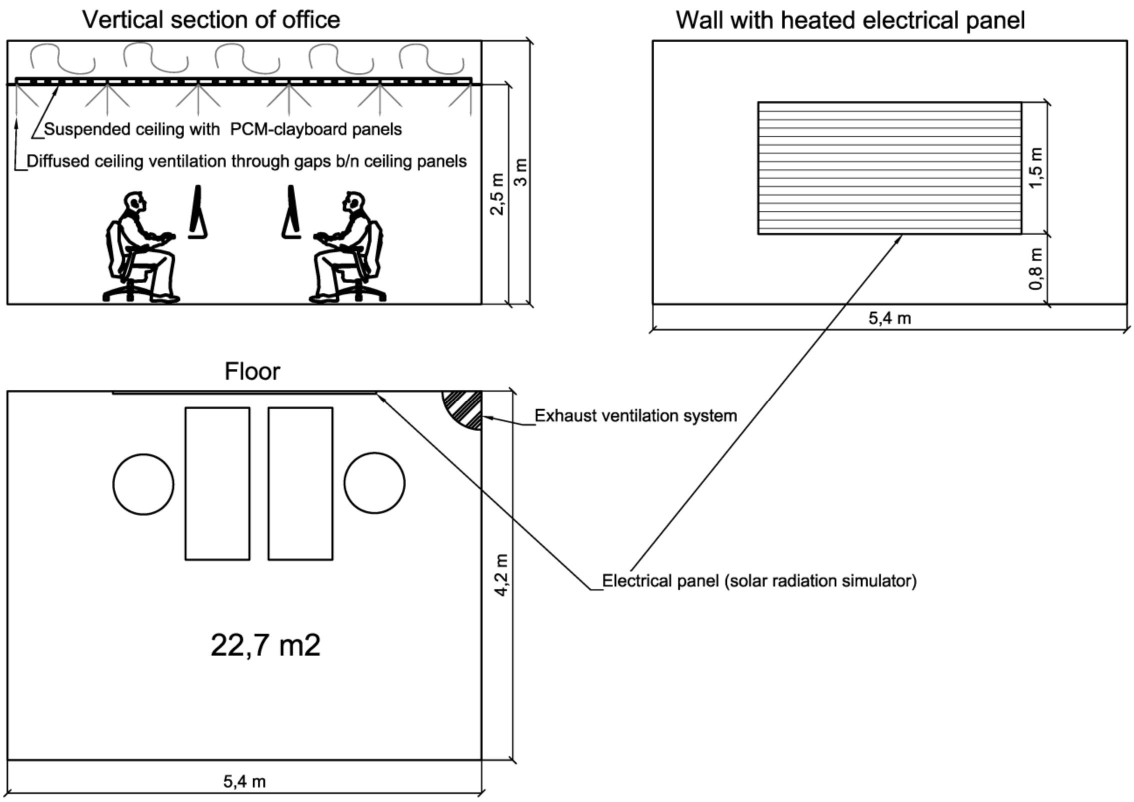


Figure 8-3: Experimental chamber layout

Figure 8-4: Experimental set-up in the climate chamber

The occupants were simulated by heated dummies. For PCs and monitors heat emitting simulators were used. The lighting was represented by electrical light bulbs hanging 30 cm from the suspended ceiling, see Figure 8-4.

Table 8-3: Internal heat gains (excl. solar)

Type of internal load	#	Heat gain per unit [W]	Total heat gain [W]
Occupants	2	75	150
PCs	2	45	90
Monitors	2	30	60
Lightning	4 el. bulbs	60	240

Solar heat gains to the indoor space were simulated in 12 min time step by electrical panel installed at one of the vertical chamber walls. Three solar heat gain profiles were simulated, P1 & P3 shown in Figure 8-5, and P4 (electrical panel was turned off) representing no solar radiation. The total resultant space sensible heat gain (solar + internal) was 250 Wh/m^2 for P1, 232 Wh/m^2 for P3, and 194 Wh/m^2 for P4.

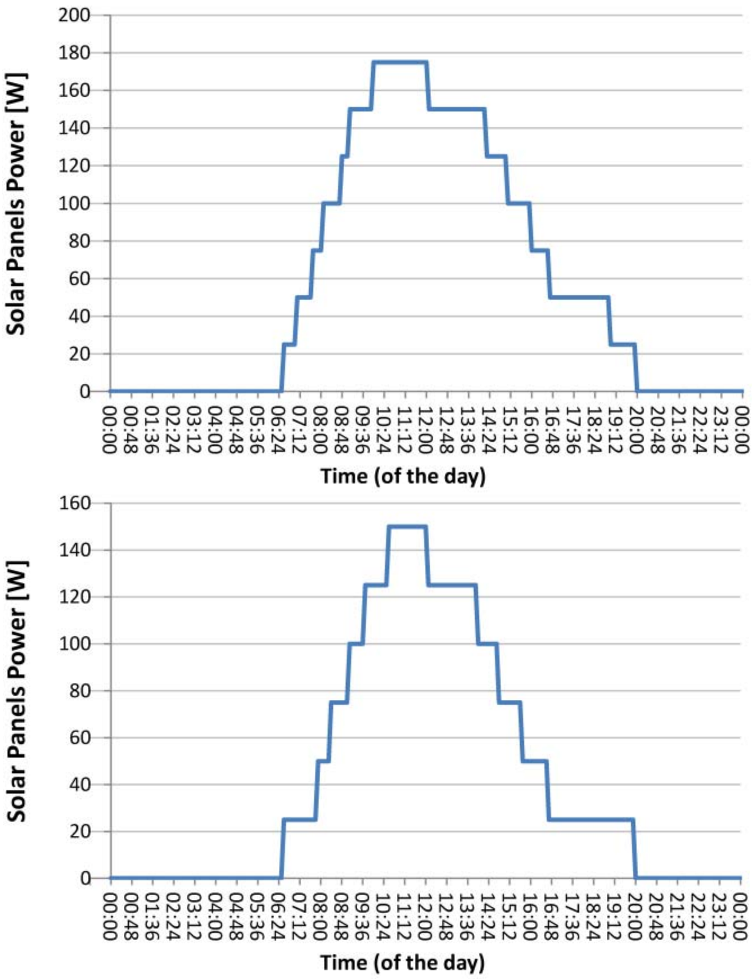


Figure 8-5: Solar radiation profiles: P1-top and P3-bottom

8.2.3 Suspended ceiling with PCM-clayboard panels

As was shown in Figure 8-4, the PCM-clayboards were installed as a suspended ceiling. Consideration was taken into account when designing the ceiling panels' layout, i.e. the hydraulic scheme. When night-time embedded pipes cooling was used, the heat gains absorbed during the day need to be extracted during night-time (from 10 p.m. to 6 a.m.) by the water circulating in the embedded pipes layer. To ensure sufficient cooling capacity, the hydraulic circuit was arranged in parallel branches, each branch consisting of 3 ceiling panels in series, Figure 8-6.

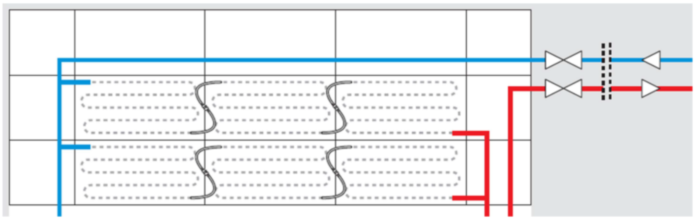


Figure 8-6: Ceiling panels hydraulic connection

Taking into account the total available ceiling area of 22.7 m^2 (4.2 x 5.3 m), and the PCM-clayboard panels dimensions of 125 x 62.5 cm, the following ceiling panels arrangement was decided, Figure 8-7.

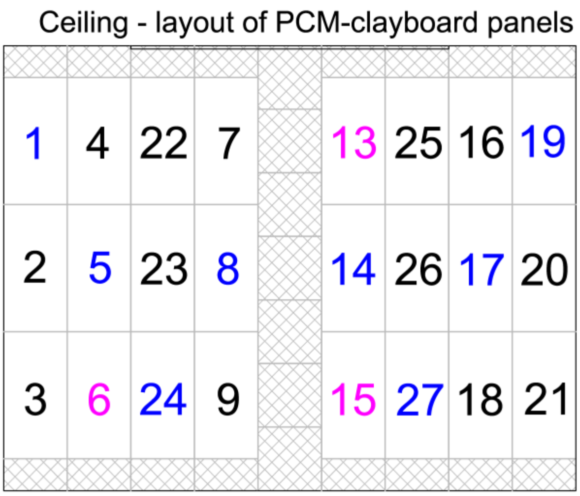


Figure 8-7: Ceiling panels' layout

In total 24 PCM-clayboard panels were installed on the suspended ceiling. Recalling the measurement results for specific heat capacity as function of temperature for the ceiling panels, shown in Figure 8-2, the total storage capacity of the suspended ceiling was calculated to 2345 Wh, for a temperature range of 20-27°C, which gives

125 Wh/m^2 panel surface. To ease the comparison with space cooling loads given in Wh/m^2, the storage capacity given per floor area was 103 Wh/m^2.

8.2.4 Ventilation system

The ventilation system investigated is a diffused ceiling ventilation type, see Figure 8-3. The space created between the suspended ceiling and the roof of the experimental chamber was used as a plenum, where the ventilation air was supplied and then directed further in the office space through the gaps between the ceiling panels. The exhaust was located in one of the corners of the camber, on the floor, see Figure 8-4. The chamber was at overpressure.

The diffused ceiling ventilation system was providing daytime ventilation from 8 a.m. to 5 p.m., flow rate of 40 l/s (2.1 h^{-1}), and supply air temperature of 18.5°C. When night-time ventilative cooling was used, the ventilation system was operated from 10 p.m. to 6 a.m., flow rate of 62 l/s (3.3 h^{-1}), and supply air temperature of 18°C. The ventilation air was supplied to the climate chamber by the main ventilation system of ICIEE Laboratory, which controlled also the supply air flow rate and temperature. The control system of the climate chamber was controlling only the daily operating schedule of the ventilation system.

8.2.5 Water supply system (for embedded pipes cooling)

The cool water is provided by a main chiller installed in the basement of ICIEE Laboratory which operates in a mode 7°C/12°C. Since this temperature was too low for the purposes of the experiment, an additional system was connected between the main chiller and the chamber (Figure 8-8). In this system the cool water passed through the circulation pump and was driven in the heater, where it was heated if necessary to reach 17°C set point for supply water temperature. Switch 1 was 20% open so there was a small circulation around the heater, in order not to burn it. Temperature sensor 1 showed the supply temperature directly after the water exits the heater. Then the water was led to the ceiling panels. Temperature sensor 2 shows the return temperature of the water coming from the ceiling panels. Depending on the water return temperature, the recirculation valve was either leading the water directly to the pump in order to be heated again, or was leading it to the network to be cooled again. The heater has three-face electric supply and nominal power of 2.3 kW. Due to that high power, the heater was not being in operation all the time. The speed of the pump is adjustable, so the flow of the water in the systems could be altered depending on the cooling demand of the panels. Moreover a one-way valve was installed in the recirculation pipe so that the cool water coming from the network will pass though the pump, and not go through the recirculation pipe in an opposite direction. Furthermore, there are two flow rate sensors in the return pipe, in order to control the flow rate of the water coming from the ceiling. Finally, switch 2 and the two regulation valves were 100% open.

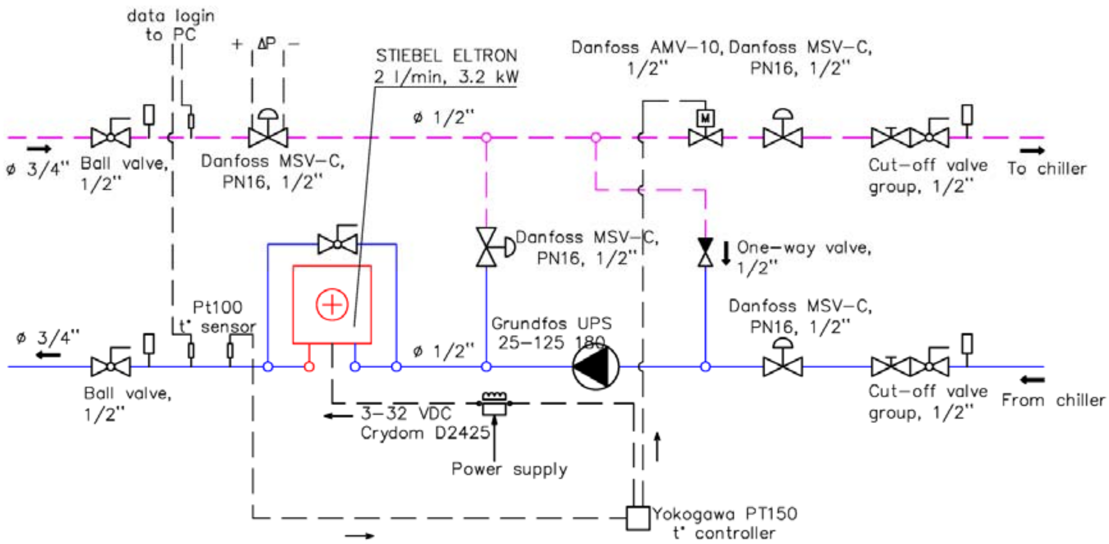


Figure 8-8: Water supply system

8.2.6 *Measured parameters*

To evaluate the performance of the PCM-clayboards and their effect on the thermal environment in the experimental office, several parameters were measured in the chamber. Although the sampling rate of recording of the control system was 1 sec, 15 min averages were used in the analysis. The measured parameters can divided in the following groups:

- Thermal environment parameters: this group includes measurement of air and operative temperature in the experimental office. Two stands with temperature sensors attached on them were placed about 60 cm behind each of the occupants' simulators, Figure 8-4 and Figure **8-9**. Air temperature was measured at 4 heights: 0.1 m, 0.6 m, 1.1 m (ankle, abdomen and head level for a seated person), and 1.7 m head level for a standing person); while operative temperature was measured only at a height 0.6 m (abdomen seated person); according to the recommendations for measuring heights of the physical parameters of an indoor environment given in EN ISO 7726 (2001). The temperature sensors were specially built for the purpose of this experiment, according to the procedure and principles given in Simone et al. (2007 & 2013), however for a sensing element Pt1000 Class A temperature sensor was used, instead of a thermocouple as was done in the cited references.

In addition to the thermal environmental parameters in the experimental chamber, air temperature in the space surrounding the chamber was measured, to give the possibility to estimate the influence of heat gains/losses due to transmission through the chamber envelope.

- HVAC system parameters: this group includes measurements of supply and exhaust air temperatures and supply air flowrate by the ventilation system, supply and return water temperature and water flowrate of the embedded in the PCM-clayboard pipes system. For ventilation air temperatures and flowrate, measurement data from the main ventilation system of ICIEE Laboratory was used. For water temperatures and flowrate, data from the water supply system was logged by the control system of the chamber.
- Internal heat gains and solar radiation: this group includes measurement of power consumption by the internal heat gains and solar radiation simulators. This data was logged by the control system of the chamber.
- Ceiling panels surface temperatures and heat flux: the parameters of this group include measurements of ceiling panels' surface temperatures and surface heat flux. For the surface temperature, Pt1000 Class A temperature sensors fixed on a small copper plate were built and attached on the ceiling panels top and bottom surfaces, Figure 8-9. Surface temperature was measured on the panels numbered with 1, 5, 8, 14, 17, 19, 24, 27, according to Figure 8-7. Surface heat flux was measured by Type M55A heat flux sensors by ETO DENKI (http://www.etodenki.co.jp), on the ceiling panel's surface facing the room, for the panels with numbers 6, 13, 15, according to Figure 8-7.

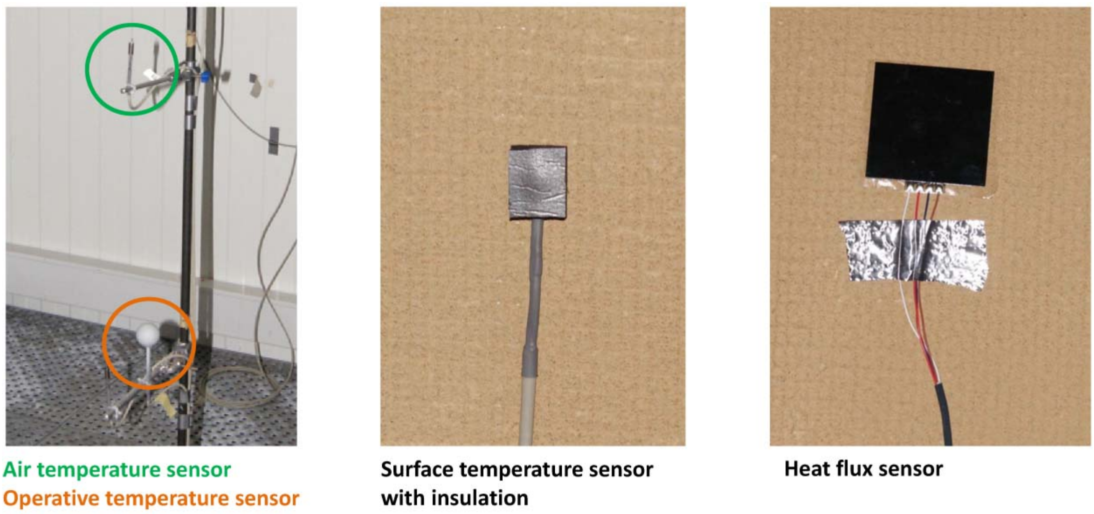


Figure 8-9: Sensors

8.3 Experimental case studies description

Two strategies of discharging of the thermal energy stored in the PCM-clayboards were used. The first strategy (experiments A - active ceiling panels scenarios), as in conventional TABS system, was to discharge the ceiling panels through the embedded pipes system during night-time. For the second strategy (experiments B - passive ceiling panels scenarios), the ceiling panels worked as passive thermal mass, the embedded pipes system was not used, and night-time mechanical ventilation was used for discharging the PCM panels.

8.3.1 Active ceiling panels – Experiments A

In the 'active ceiling panels' scenarios, the PCM-clayboard ceiling panels were discharged through the embedded pipes system during night-time. Water flow rates and supply temperatures are summarized in Table 8-4.

The night-time operation of the embedded pipes system was 'ON' from 10 p.m. to 6 a.m., with constant water flow rate and supply temperature. The system was in 'ON' state until the time was over (6 a.m.) in order to ensure complete solidification of the micro-encapsulated PCM in the ceiling panels. Three different solar radiation profiles were used, as described in the "internal heat gains section".

8.3.2 Passive ceiling panels – Experiments B

In the 'passive ceiling panels' scenarios, night-time ventilation was used for discharging the thermal energy stored in the ceiling panels during the occupancy hours. Ventilation flow rates and supply temperatures are summarized in Table 19. By supplying the air through the ceiling plenum, high air change rate and respectively high convective heat transfer between the PCM-clayboard panels and the air in the plenum was achieved, which was expected to result in efficient discharging of the stored thermal energy.

The night-time ventilative cooling was 'ON' from 10 p.m. to 6 a.m., with constant air flow rate and supply air temperature. The night-time ventilation was working during the whole period and there was no control over preventing too low indoor temperatures at the end of the cooling period. Three different solar radiation profiles were used, as described in the "internal heat gains section".

8.3.3 Summary of experimental scenarios

Three 'active ceiling panels' experimental scenarios were investigated, where only the solar heat gains to the space were varied. The same boundary conditions were used for the investigated three 'passive ceiling panels' experimental scenarios. Summary of the experimental case studies is given in Table 8-4.

Table 8-4: Summary of experimental case studies

Experiment label	A1	A3	A4	B1	B3	B4
Water flowrate [kg/h]	150	150	150	-	-	-
Supply water temperature [°C]	18.5	18.5	18.5	-	-	-
Vent. Flowrate day [l/s]	40	40	40	40	40	40
Supply air temp. day [°C]	18.5	18.5	18.5	18.5	18.5	18.5
Vent. Flowrate night [l/s]	62	62	62	62	62	62
Supply air temp. night [°C]	18	18	18	18	18	18
Solar heat gain profile	P1	P3	P4 (no solar)	P1	P3	P4 (no solar)

8.4 Measurement results

Continuous measurements for several consecutive days were done for each of the experimental case studies. Measurement results for two days are presented in the present section of the thesis.

8.4.1 Indoor air and operative temperatures and ceiling panels' surface temperatures

In Figure 8-10 are shown the indoor air and operative temperature variation in the climate chamber during two consecutive days for each of the experimental case studies. In addition, the temperature measured outside the chamber is shown as well (indicated as T_e on the graphs). For the experiments with the highest internal heat gains, A1 (active panels) and B1 (passive panels) somehow similar results for the indoor temperatures are obtained, with about 0.3K lower values for the case with active panels. For experiment A1, the indoor operative temperature varied in the range 22.7-28.7°C (6K daily variation), while for experiment B1, the daily variation was 23-29°C (6K daily variation). The vertical temperature difference between 0.1 m and 1.7 m was about 0.9K in both experiments.

For the experimental case studies with medium and low internal heat gains, the passive panels' concepts performed better that the concepts with active panels in terms of room temperature control. For experiment A3, the indoor operative temperature varied between 22.4-27.9°C (5.5K daily variation), compared to a daily variation of 22-27°C (5K daily variation) in experiment B3. In experiment A4 the daily operative temperature variation was 22-26.3°C (4.3K daily variation) and in experiment B4 it was 21-25.4° (4.4K daily variation). The vertical temperature difference between 0.1 m and 1.7 m was about 0.6K in the four experiments.

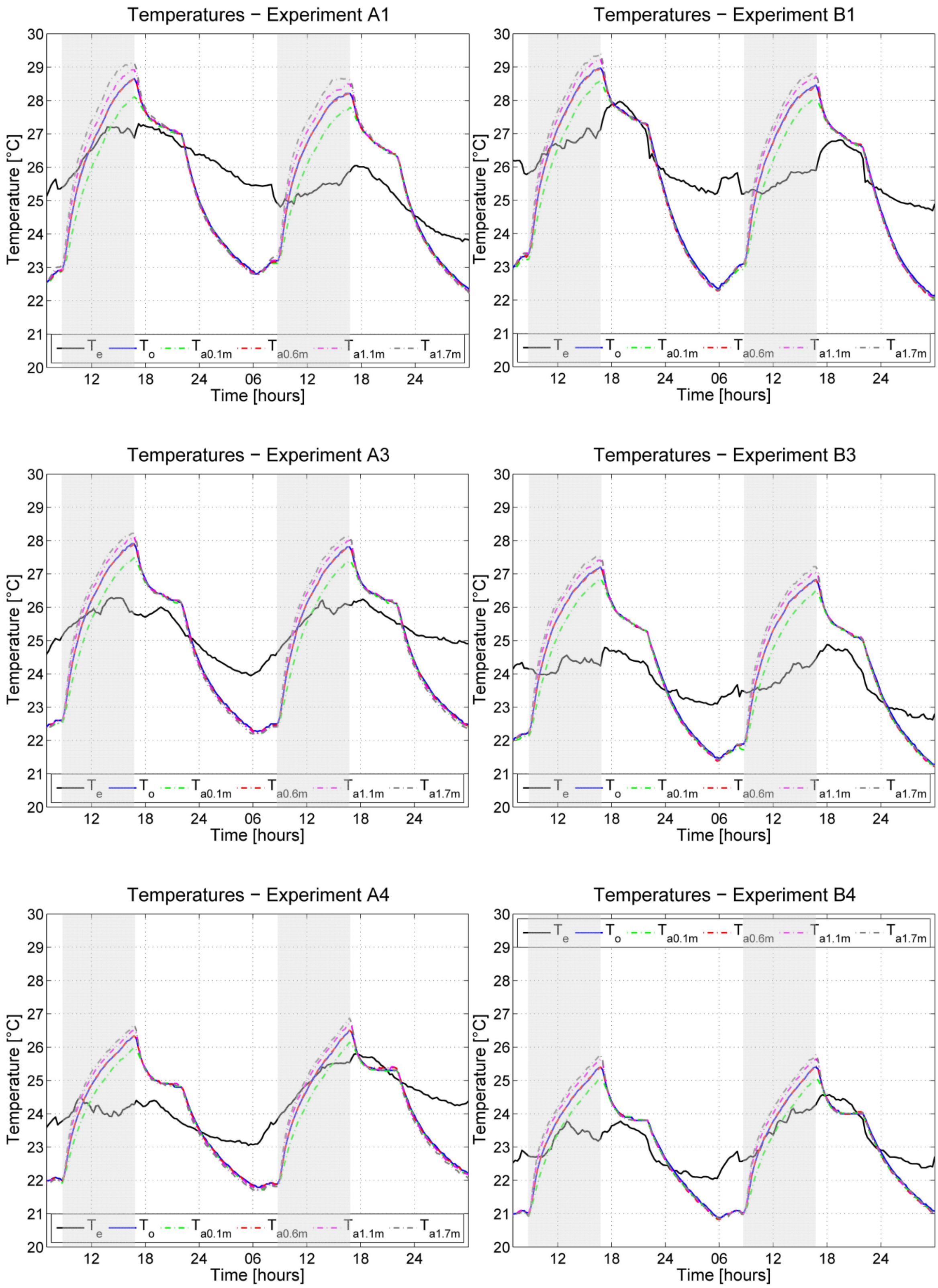


Figure 8-10: Air and operative temperatures, all case studies (occupancy hours in shaded area)

The reason for the lower maximum indoor operative temperature obtained in the experiments with passive ceiling panels could be explained with the fact that in these experiments the climate chamber was cooled down to a lower temperature at night, about 0.5K lower in B3 compared to A3, and about 1K lower in B4 compared to A4. To check if these lower indoor temperatures have resulted also in a better discharge of the PCM-clayboard ceiling panels, the surface temperature variations of the ceiling panels are shown in Figure 8-11, Figure **8-12**, and Figure **8-13**.

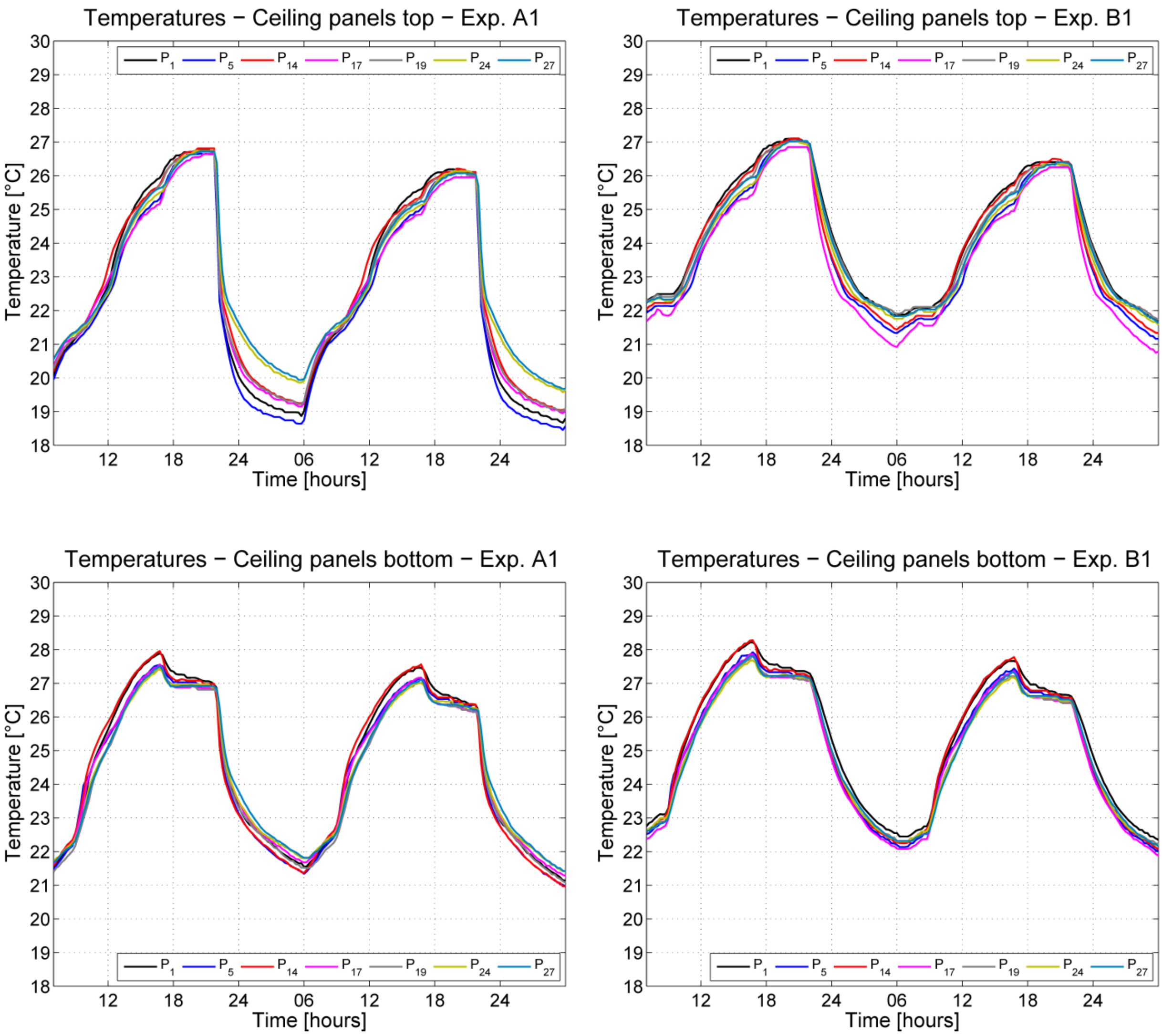


Figure 8-11: Ceiling panels surface temperature, experimental case studies A1 and B1

Comparing the surface top (facing the roof) and surface bottom (facing the room) temperature variations in experiments A1 and B1, can be seen that the local discharging of the ceiling panels with the embedded pipes system results in lower temperatures compared to the night-time ventilative cooling which was insufficient to discharge the thermal energy stored in the ceiling panels. These results suggest that the ceiling panels in Experiment A1 should have been almost completely discharged and more ready to absorb internal heat gains on the following day, and eventually that could have been the cause for the slightly lower indoor temperatures obtained (0.3K). Considering that the top and bottom ceiling panels' surface temperatures in both experiments have reached values up to 27°C suggest that the complete storage capacity of the panels was utilized. The panels top and bottom surface temperatures were higher than 25°C (upper melting temperature range of the PCM) already about 2-3h before 5 p.m. (end of occupancy period), which suggests that for such internal heat gains intensity, higher storage capacity in the ceiling panels could have been more beneficial.

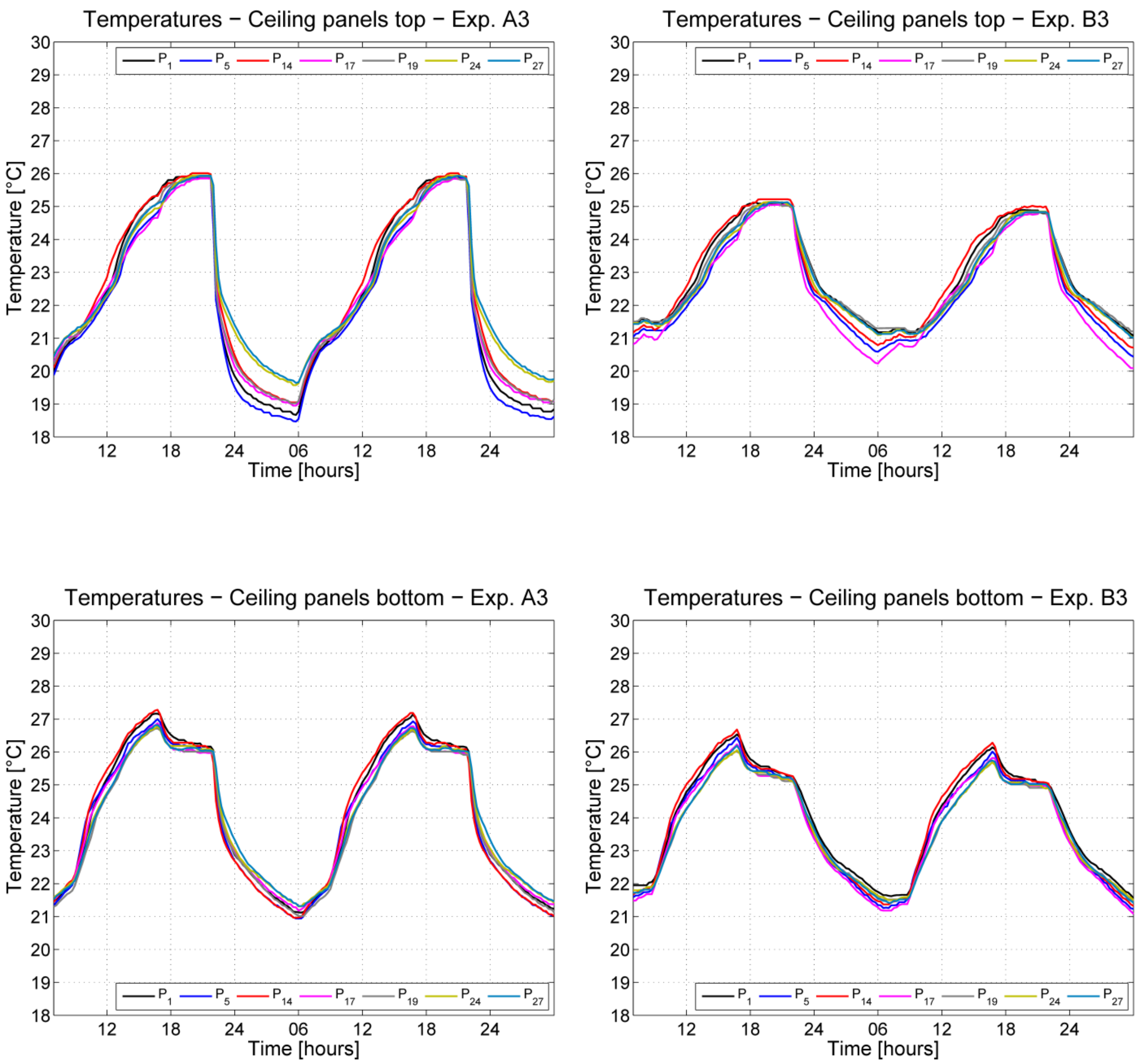


Figure 8-12: Ceiling panels surface temperature, experimental case studies A3 and B3

For experiments B3 and B4, the night-time ventilative cooling was with sufficient capacity to discharge the PCM-clayboard ceiling panels (panels' surface top and bottom temperatures brought down to 21.5°C and 20.5°C on average), resulting in similar surface temperatures compared to the experiments with active night-time discharging A3 and A4. That in addition to the lower indoor temperatures measured at the end of the nigh-time cooling period in experiments B3 and B4 resulted in better room temperature control compared to the results in experiments A3 and A4.

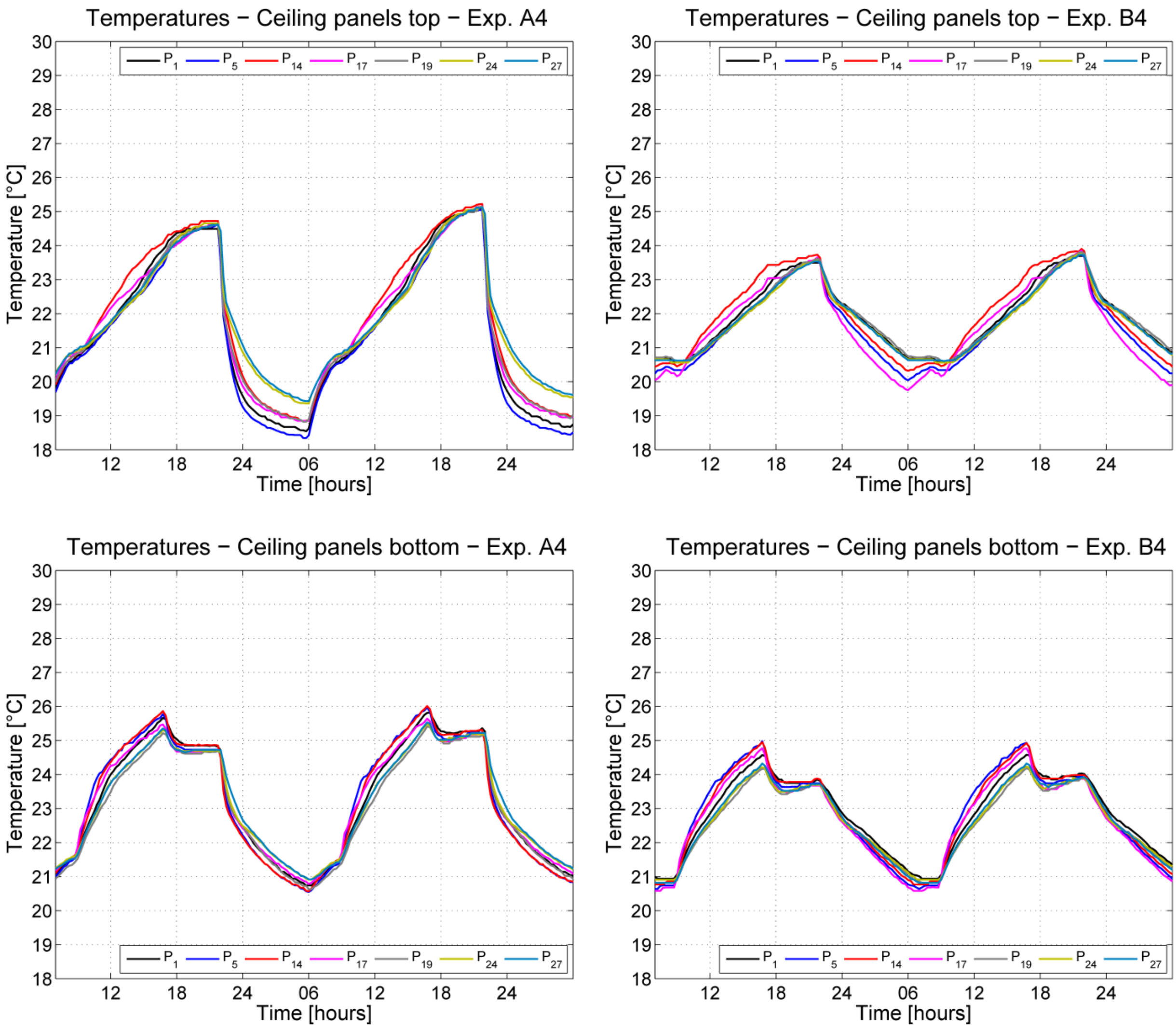


Figure 8-13: Ceiling panels surface temperature, experimental case studies A4 and B4

Considering that the top and bottom ceiling panels' surface temperatures in experiment A4 and B4 are within or below 25°C within the occupancy hours suggest that the ceiling panels' storage capacity was not completely utilized and has been sufficient to cope with the internal heat gains intensity in these experiments. That was very pronounced especially in experiment B4.

8.4.2 Ceiling panels surface heat flux and thermal energy storage capacity utilization

In Figure 8-14, the heat sources location in the climate chamber, represented by the red shaded area in the semicircle, is shown with respect to the ceiling panels' layout. The surface heat flux, measured on ceiling panels 6 and 13, for all six experimental case studies is shown in Figure 8-15. That heat flux measurements can be used to calculate the thermal energy stored in the ceiling panels during the day. However, should be kept in mind that, although it is a good indicator, the so calculated stored in the ceiling panels thermal energy may not be necessarily very precise for the particular experimental set up.

The first issue under consideration, when the surface heat flux is used for thermal energy storage calculation, is that it was measured only on two ceiling panels. In the used experimental set-up, the ceiling panels located above the heat gains simulators should have absorbed more thermal energy, resulting in higher surface heat flux, due to the thermal plumes from the heat sources and increased radiative and convective heat exchange. In that way of thinking, the surface heat flux on panel 13 should have been higher than on panel 6, and that expectation was partly confirmed by the measurement results shown in Figure 8-15.

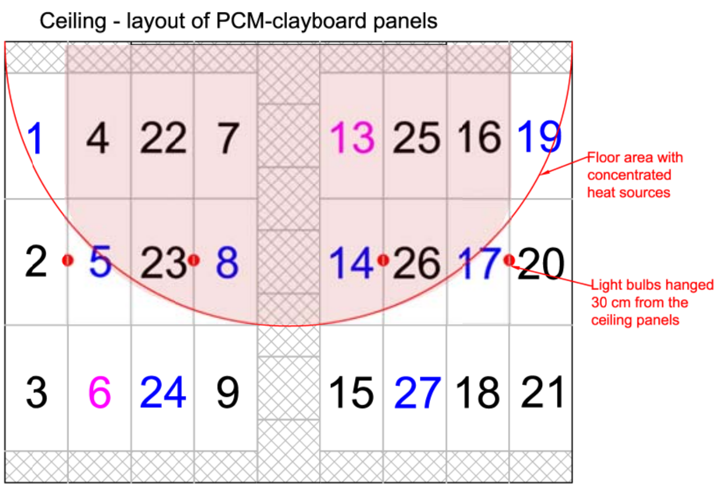


Figure 8-14: Internal heat gains simulators location with respect to ceiling panels' layout

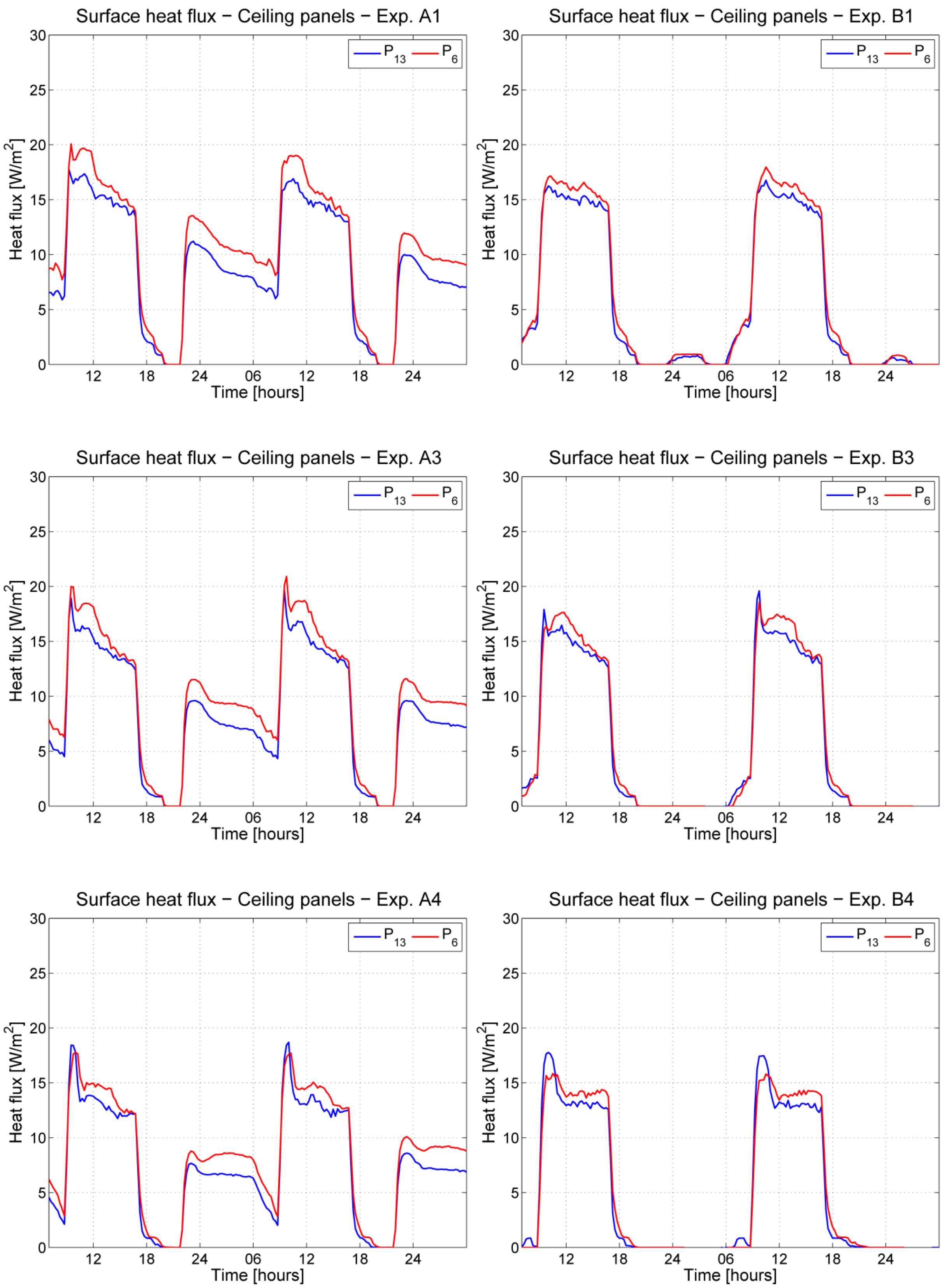


Figure 8-15: Ceiling panels surface heat flux, all experimental case studies

The second issue that should be considered is that the PCM-clayboard panels were a structural part of the ventilation system plenum, built between the experimental chamber's ceiling and the suspended ceiling. In that way, the top surface of the ceiling panels was in direct contact with the supplied cool air by the ventilation system. There has been a continuous heat transfer between the ceiling panels and the ventilation air, however since there were no heat flux sensors installed on the top side of the ceiling panels, no estimate can be given on the amount of thermal energy extracted from the ceiling panels by heat exchange with the supply ventilation air. Using the heat flux measured on the bottom surfaces of the ceiling panels for calculating the stored in them thermal energy can result in an overestimation of the actual stored energy.

However, since the differences in the measured heat flux are relatively small, and although not entirely accurate due to the used ventilation system concept (suspended ceiling plenum), a representative estimation of the stored thermal energy can be calculated from the surface heat flux measurements. In Table 8-5 are given the calculated amounts of stored thermal energy in the PCM-clayboard ceiling panels, for the six experimental case studies, and compared to the maximum storage capacity of the ceiling panels. The given values are per m^2 ceiling panel's area. The results suggest that in all experimental case studies, there was a good utilization of the thermal mass in the PCM-clayboard ceiling panels.

Table 8-5: Stored thermal energy in the PCM-clayboard ceiling panels (per panel area)

Experiment	A1	A3	A4	B1	B3	B4	Storage capacity
Stored thermal Energy Wh/m^2	124	118	108	120	118	110	**125**

8.5 Experimental evaluation versus computer simulation modeling

In Chapter 5, parametric study on the thermal performance of PCM-gypsum panels was performed through computer simulations using TRNSYS 17. The bases for development of this simulation model were used here to develop a computer simulation model of the climate chamber used in the experimental study. By comparing the measurement results from the experimental study and simulation results from the computer model would give an idea of the prediction capabilities and accuracy of representation of the climate chamber by a simulation model. In the present section, the assumptions made for building the computer simulation model are presented. Additionally a comparison between the experimental and simulation results is done, in terms of indoor operative temperature and ceiling panels' surface temperature variation, surface heat flux and stored thermal energy in the ceiling panels.

8.5.1 Simulation model

Two computer simulation models of the climate chamber were implemented in TRNSYS 17. One representing a passive ceiling panels model with night-time ventilative cooling, with internal heat gains and HVAC system control identical to experimental case study B4. The second model represented active ceiling panels with embedded pipes night-time cooling and had internal heat gains and HVAC system control identical to experimental case study A4. Both models actually were identical, with the only difference being the night-time cooling principle: night-time ventilation vs. embedded pipes.

The simulation models comprised of two thermal zones, one representing the occupied office space and the other representing the ventilation plenum built between the suspended ceiling and the roof of the chamber.

Data on the envelope of the climate chamber was gathered through investigation of the external walls structure, comprised of steel sheet cladding on the external and internal side of the walls and 10 cm of insulation. An estimated heat transmission coefficient of 046 W/m^{2}K was used in the simulations.

The internal heat gains in the simulation models were assumed to be 50% convective and 50% radiative gains. The thermal loads had identical daily profile as in the experimental case studies. The measured, during the experimental studies, temperature variation around the climate chamber was used as outdoor temperature variation in the simulation models.

For modeling the PCM-clayboard ceiling panels, data on the thermal properties of the composite panel was required. The experimentally determined specific heat capacity as a function of temperature (Figure 8-2) and PCM-clayboard panels' thermal conductivity (Table 8-2) were used in the simulations. The ceiling panels were modeled as built of homogeneous material having the experimentally determined thermal properties, and that structure was different from the actual layered construction of the panels (Figure 8-1).

8.5.2 Comparison between simulations and measurements

A comparison between the experimental and simulation results, for case studies A4 and B4, is shown in Figure 8-16. The shown parameters are for 1 day period and include the indoor operative temperature, the ceiling panels' surface temperature (average value of the measurements for several panels), and the panels' surface heat flux.

The indoor operative temperature variation (Figure 8-16 – top) obtained from the computer simulation models show similar curvature and amplitude of variation during the day. For case study A4, the measured results are slightly higher, with a daily maximum of 0.8K higher than the simulation values, while for case study B4, minor difference of 0.2K was noticed.

For the ceiling panels surface temperature (Figure 8-16 – middle) quite identical results for case study B4, with passive panels and night-time ventilative cooling, were obtained. For case study A4, with active panels with embedded pipes night-time cooling, the simulation model predicts somehow lower amplitude in the variation of the panel's surface temperature compared to the measurement results, with 0.5K higher minimum morning values, and 1K lower maximum afternoon values.

A comparison between the measured surface heat fluxes on two of the ceiling panels with the surface heat flux obtained from the computer simulations, for both case studies A4 and B4, show relatively similar values (Figure 8-16 – bottom). There are some differences during night-time cooling period and the first 1-2 hours of the occupancy period, where the simulation models have predicted lower surface heat flux.

The thermal energy stored in the ceiling panels, for the different simulation and experimental case studies, are shown in Table 8-6. Although the numbers are quite close, the results suggest that the simulation model predicts slightly higher stored thermal energy.

Table 8-6: Stored thermal energy – measurements vs. simulations

Case study	A4 – exp.	A4 – sim.	B4 – exp.	B4 – sim.
Stored thermal energy (Wh/m^2)	108*	113	110*	116

*calculated form surface heat flux

It is seen from the above presented results that the simulation models represent quite well the actual situation in the climate chamber. There are some differences encountered, more pronounced in case studies A4. However, it should be mentioned, that the achieved accuracy in prediction by the simulation models is quite satisfactorily, having in mind the number of assumptions made and of uncertainties encountered while building the simulation model.

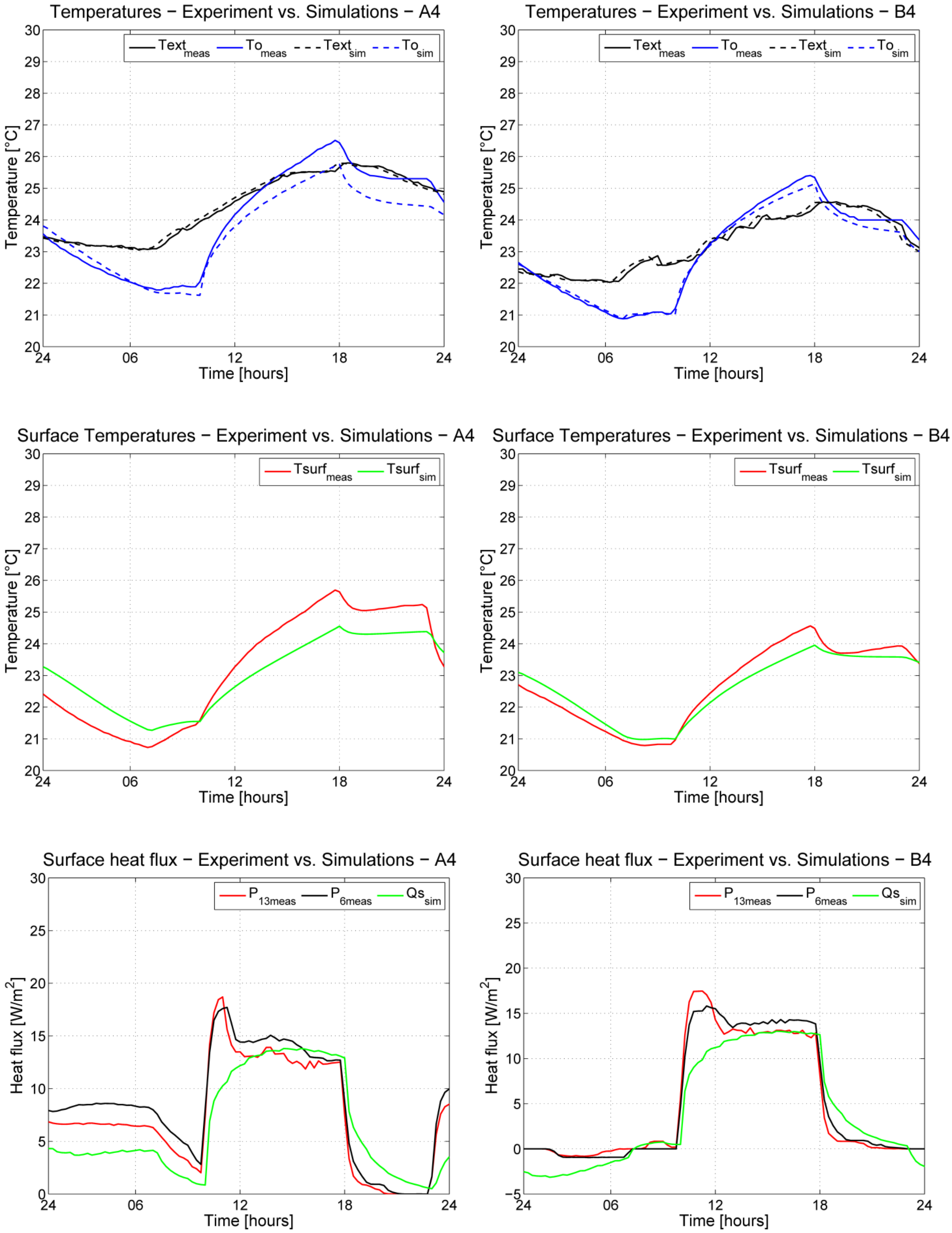


Figure 8-16: Comparison between simulation models and experimental results, case studies A4 and B4

A factor that was not discussed until now, and should be mentioned due to its possible influence, is the way the indoor space is represented in the simulation model. The experimental chamber is represented as a single air-node in the TRNSYS model, and in that way all internal heat gains are homogeneously exerted on the ceiling panels which mean that the whole ceiling area is exposed to same thermal conditions. That is not the case in the experimental case studies, where due to the location of heat sources, different areas of the suspended ceiling will be exposed to different thermal conditions. The same concerns are valid also for the night-time ventilative cooling and the night-time embedded pipes cooling.

8.6 Summary

The performance, in terms of temperature control and cooling load management, of PCM-clayboard ceiling panels was evaluated for a simulated office environment in a climate chamber. Six experimental case studies were established, three with active ceiling panels and three with passive panels. Different internal heat gains intensity were used in the different case studies.

The measurement results suggest that for cooling loads of 250 Wh/m^2 (experiments A1 and B1), about 100 Wh/m^2 could be stored in the ceiling panels. For cooling loads of 232 Wh/m^2 (experiments A3 and B3) about 98 Wh/m^2 of the cooling load stored in the PCM-clayboard ceiling panels and for cooling loads of 194 Wh/m^2, about 91 Wh/m^2 were stored in the panels.

Results from the experimental study have shown that about 40 – 47% of the daily cooling loads were stored in the PCM-clayboard ceiling panels, and shifted to night time. Since the operation of the night-time cooling in all experimental case studies was not optimized for energy savings, but rather was forced to operate in a continuous manner so as to discharge as good as possible the ceiling panels, no analysis on peak-load shifting and energy savings were done. In terms of temperature control, the ceiling panels were an efficient solution for cooling loads of up to 232 Wh/m^2.

In terms of temperature control during hours of occupancy, for experiments A1 and B1 the resultant indoor operative temperature variation was in the range of 23 – 28.5°C (5.5K) and 23 – 28°C (5K) respectively. For experiments A3 and B3 the temperature variation was 22.5 – 28°C (5.5K) and 22 – 27°C (5K). And for experiments A4 and B4 the variation was 22 – 26.5°C (4.4K) and 21 – 25.4°C (4.4K) respectively. It can be seen from the results that the daily amplitude of operative temperature variation was between 5.5K and 4.3K, with the values decreasing with decrease of the thermal load. For cases B3 and A4, the indoor operative temperature variation falls between the comfort limits of the standard. For experiment B4, the maximum afternoon temperatures were 1.5K below the recommended limit. In the morning hours, 1K lower temperatures than recommended were measured, however the comfort limit was reached in about 1h time. If these low morning temperatures are considered unacceptable, additional control over the night-time cooling should be imposed. To optimize the system performance in case B4, but also in the other experimental case studies, control over the minimum allowed indoor temperature during night-time cooling would have helped to avoid cooler environment during morning hours of occupancy.

If the thermal comfort criterion for Category III from Standard EN 15251 was to be fulfilled, the indoor operative temperature in the experimental chamber should have been in the range 22 – 27°C. It can be seen that in cases A1, B1 and A3 that criteria was not fulfilled, and the daily temperatures were shifted to about 1-1.5K higher values. Higher rates of night-time cooling and additional supplementary cooling by the ventilation system during daytime could have helped to improve the thermal conditions in the chamber.

The results from the experimental study were compared with results from a computer simulation model, in order to evaluate the accuracy of the predicted behavior of PCM ceiling panels through computer simulations. Results for operative temperature, ceiling panels surface temperature and heat flux, and stored in the ceiling panels thermal energy were compared. It was shown that the simulation models represent the actual situation in the climate chamber quite satisfactorily, with some minor differences encountered in the different case studies.

PART V: SUMMARY AND CONCLUSIONS

This part summarizes the work from all parts in this thesis, including discussion on the main findings, final conclusions from the work and suggestions for further study.

9. Summary and conclusions

9.1 Summary and discussion of Part II

The main objective driving the development and utilization of thermal energy storage systems for space heating and space cooling applications is to overcome the mismatch between thermal energy availability and demand. In the literature review study done in Part II of the thesis are presented the findings and operational experiences of different seasonal and diurnal TES systems and concepts.

9.1.1 Seasonal TES in the ground

The concept for seasonal thermal energy storage in the ground has found two main applications, to store solar heat collected in summer for space heating in winter, or to provide heating and cooling by storing heat underground in summer and removing heat in winter.

The seasonal storage of solar heat has been aimed at heating large district system stores part of CSHPSS, utilizing water tanks, water-gravel pits, borehole fields and aquifers as ground storage reservoirs. Storage construction costs were identified among the main challenges to make these technologies economically competitive against conventional energy sources.

The different concepts have shown technical feasibility and solar fractions of 25-50% of delivered heat. The results from the monitoring campaigns at different solar plants have shown that, in order to achieve high solar energy efficiency, limit thermal losses and improve solar collector efficiencies, the solar plants have to be operated at low temperatures. Low temperature concepts with the use of heat pumps and of low-temperature heating systems (like floor heating) in the buildings were appropriate solutions.

Summarizing the findings from computer simulation studies and monitoring campaigns it can be noted that, in addition to the seasonal storage itself, the seasonal solar energy storage technologies are dependent on many factors such as solar collectors, annual sun exposure, heat distribution networks, heat demand and insulation of the buildings, and the seasonal thermal storage requirements.

The use of ground-coupled heat pump systems in buildings offers economic and environmental advantages when both heating and cooling is required. These double-effect storage projects have shown to be more beneficial since the ground-coupled system can function both as a heat source and a heat sink. Additionally, the double-effect storage concept also can make sure that the ground temperature over years will not change significantly compared to if only cooling or only heating was used. The ground storage concepts utilized were borehole TES and aquifer TES.

Experiences from pilot projects and demonstration plants have shown storage efficiencies of 60 to 90% and primary energy savings of 20 to 70%, with estimated payback periods of 8 to 12 years.

These seasonal TES systems have shown increased efficiency when used in combination with low-temperature heating and high-temperature cooling radiant systems in the building, like TABS and floor heating/cooling systems.

Regardless of the high energy saving potential and the intensive technological development in recent years, GSHP systems have been obstructed by the high investment costs associated with the ground storage, especially for borehole ground storage. Alternative designs for ground-source systems, like hybridization, have been investigated. This approach, utilizes the use of a cooling towers or boilers for handling peak heating and cooling loads, and thus allows the seasonal ground storage to be sizes for smaller thermal loads. In that way, the capital costs associated with constructing the ground storage can be reduced, however on the expense of reducing the potential energy saving capacity of the system.

9.1.2 Diurnal TES in building's thermal mass

In the literature review extensive research surveyed on passive and active building thermal mass utilization was presented. Most of the studies consider the thermal mass utilization for cooling load management, due to the higher efficiencies in comparison to heating load management. Office- or other buildings that are unoccupied during the night-time have been identified as most suitable for utilizing their thermal mass, due to the possibility to use the night hours to cool the building structure in order to prepare the building for the following day.

Cooling by night-time natural ventilation has been identified as one of the most efficient applications of thermal mass. The concept can reduce the indoor maximum operative temperature, reduce the cooling energy demand, and offset the peak cooling loads. Thermal mass combined with night-time natural ventilation may reduce the maximum indoor temperature by 2-6 K if night temperatures are low enough to release the heat from the building's thermal mass. Appropriate diurnal outdoor temperature variation should be at least 10 K and the minimum night-time outdoor temperature in summer should be below 20°C in order to achieve the desired cooling effect.

Depending on the climate and type of building, the cooling energy savings found in the literature span from 5 % to 36 %. Moreover, if building's heat gains are not too excessive, thermal mass and night ventilation should be sufficient to cover the cooling demand in moderate climates alone, without the need of air-conditioning.

When high outdoor temperatures persist for long periods, passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. In these cases mechanically supported night-time ventilation can be utilized. In that case the energy savings potential in terms of primary energy savings is reduced or not present at all due to the use of a mechanical system. Some studies have shown even that when the night-time mechanical cooling is not properly controlled, higher energy use may result in comparison to a conventional cooling system. Regardless of the low primary energy savings potential, there are other benefits associated with the shifting of part of the daily cooling loads to night-time. Load shifting allows energy costs reductions through the use of low cost off peak electricity rate, more favorable ambient operating conditions, and reduction of peak electricity demand. Results from the different simulation and experimental studies have shown peak electricity use reductions of 10-35% and cost saving due to time-of-use electricity tariffs of 10-50%. Night-time ventilation and HVAC system control strategies, occupancy periods, internal gains, and the presence of time-of-use electricity tariffs were of utmost importance for achieving these benefits.

Thermo active building systems are considerably more effective in terms of climate dependence, due to the active utilization of the thermal mass. Shifting the heating and cooling loads to off-peak hours lowers the operating costs of these systems. In addition, the temperature of the cooling/heating medium can be close to desired room temperature which opens high potential for using renewable energy sources (ground source heat pumps, ground heat exchangers etc.). Furthermore, the storage of part of the heating/cooling load in the building structural mass allows designing the heating/refrigeration equipment for lower maximum thermal load, which offers further cost savings due to downsizing of the mechanical equipment.

Barriers for the widespread application of TABS are related to the fact that the system is suitable for buildings with low heating (10-30 W/m^2) and cooling loads (30-60 W/m^2). That makes TABS system particularly suitable to buildings with high level of insulation, efficient solar shading, and low to moderate level of internal heat gains. Additionally, due to the exposed ceiling slabs without the use of suspended ceiling could cause problems related to solving the acoustical requirements in the building.

Regardless of the mentioned challenges in terms of thermal load limits and acoustics, TABS system have found widespread application in Europe, and have shown satisfactorily performance. Major challenges are related to the need for optimization of the system control strategies in the first year of system operation.

Common consideration, when building's thermal mass is utilized for temperature control and thermal load management is the fact that in these buildings cannot be expected to keep a fixed temperature. Building occupants' thermal comfort at drifting operative temperatures is playing significant role in systems' acceptance.

9.1.3 PCM enhanced building thermal mass

There has been increased interest in recent research on the use of PCM in building materials and components for increasing the thermal mass of lightweight buildings. Phase change materials have the potential for storing much larger amounts of thermal energy per unit mass or unit volume, compared to conventional building materials like gypsum, bricks and concrete, by storing the thermal energy as latent rather than as sensible heat.

By summarizing the findings in literature it was shown that the efficient utilization of PCMs for use in building materials and components are dependent on properties like fusion temperature and latent heat of fusion, behavior during melting/solidification, fire hazards, cost and availability, long term stability, and methods for incorporation in building materials and components.

In terms of long term stability, organic PCMs like paraffin have shown strong advantages compared to inorganic PCMs (salt hydrates) in terms of physical and chemical stability, good thermal behavior, adjustable transition zone, and no supercooling. However, those materials are more costly than common salt hydrates; they have lower heat storage capacity per unit volume, and have poor fire hazard characteristics due to their flammability.

The development of PCM microencapsulation has been a significant breakthrough in the incorporation of PCMs into building components such as gypsum boards, plasterboards, floor tiles, bricks, and concrete. This technology has helped to solve problems related to the low thermal conductivity of PCMs, leakage through the pores of the carrying building material and incompatibility between the PCM and that material. However, cost issues related to the microencapsulation process represent a substantial barrier for the widespread adoption of these applications.

Selecting a suitable PCM for incorporation in building materials and components for thermal mass enhancement is a complicated process. The potential PCMs should have a suitable melting temperature and desirable heat of fusion. To be able to provide efficient room temperature control, in building thermal mass enhancement applications PCMs' melting temperature should be in the comfort temperature range. PCMs with a phase change temperature (18 - 30°C) have been considered to meet the needs of thermal comfort. The optimal melting temperature may also be different from heating to cooling season, which is an additional complication. In order to keep the indoor temperature in the comfort range for long time (e.g. a day) without or with decreased heating and cooling load, the heat of fusion of a PCM should be high enough so as to keep the wall's inner surface at the melting temperature for up to a whole day.

Plasterboard is identified as the most widely used wall and ceiling lining material in lightweight buildings or during refurbishment of existing ones. Use of PCM-plasterboards instead of conventional plasterboards has the potential for increasing the thermal mass of lightweight buildings or adding such during renovations. The added thermal mass can help to avoid overheating problems in such buildings and reduce or shift energy consumption, as was discussed in the section on thermal mass. In terms of long term stability, leakage problems avoidance and thermal conductivity issues, the incorporation of micro-encapsulated PCM in plasterboards has shown the highest potential.

Plasterboards with incorporated microencapsulated PCM, for thermal mass enhancement and room temperature control, have been studied experimentally and in numerical simulations. Most of the studies concentrated on passive PCM-plasterboards, however plasterboard panels with embedded pipes or capillary tubes for active thermal load management have been considered as well. The published results have shown significant potential for decreasing the diurnal temperature swings and peak daytime temperatures, in comparison with conventional plasterboards.

PCM fusion temperature, amount of PCM used, permitted indoor temperature variation, and thermal conductivity of the PCM-plasterboard composite the have been identified as the most important parameters influencing the efficient utilization of the added thermal mass in terms of room temperature control and peak load management.

9.2 Summary and discussion of Part III

The main objectives of the parametric study was to assess the efficiency and potential benefits of the use of phase change materials in building materials and components to enhance the thermal mass of lightweight buildings. For this purpose, a computer simulation model in TRNSYS 17 was employed. The indoor space simulated was a 2-persons office room, located on a middle floor of a lightweight office building with high standards for insulation and air tightness. The evaluation was performed in terms of summertime temperature control and cooling load management (peak shaving and shifting of the daily cooling loads to night-time).

Use of passive PCM-gypsum ceiling panels combined with night-time natural ventilation were assessed for the moderate summer climate of Copenhagen, Denmark, while PCM-gypsum active ceiling panels with embedded pipes for night-time cooling were considered for the hot summer climate of Madrid, Spain. The parameters evaluated were the PCM fusion temperature, PCM-gypsum thermal conductivity, and cooling load daily profile and intensity.

From the investigated PCM fusion temperatures, the importance of this parameter in terms of room temperature control was revealed. Having the same heat storage capacity, ceiling panels with PCM 23 (21-25°C melting range) showed best capabilities in keeping the indoor operative temperature within the comfort limits of 22-27°C (Category III, EN 15251). For ceiling panels with PCM 21 with lower fusion temperature (19-24°C), too low temperatures were reached in the morning hours of occupancy due to the need to cool the ceiling panels to lower temperature during night-time in order to extract from them the store heat from the previous day. When ceiling panels with PCM 26 (24-28°C melting range) were used, their thermal storage capacity was activated at higher room temperature resulting in many hours with overheating. Moreover, it was revealed the advantage of local discharging when active ceiling panels with PCM with lower melting temperature were used. In that case, due to the use of the embedded pipes system, the resultant operative temperature in the office in the early morning hours was closer to the comfort limit compared to when night-time ventilative cooling was used.

In the literature review study was revealed that PCM-gypsum boards with a higher thermal conductivity are likely to perform better, due to the higher rates of absorbing heat during PCM melting and of releasing heat during PCM solidification. In the parametric study three different thermal conductivities of the PCM-gypsum composites were investigated: 0.19 W/mK, 0.38 W/mK, and 0.76 W/mK. Increasing the thermal conductivity resulted double and four times resulted in 0.4K and 0.6K decrease of the maximum operative temperature in the office space, for the building model with passive ceiling panels, and in 0.3K and 0.5K decrease for the case with active ceiling panels. In terms of utilized ceiling panels' thermal mass, the improvement was in the range of 3-9% in all simulation case studies. A tendency for slight increase of the benefit of higher thermal conductivity was noticed for space cooling loads with higher intensity.

The obtained results show minor benefits of the increased thermal conductivity for the studied range. These results are partly attributed to the heat-absorption rate (thermal diffusivity) dependence of the PCM-gypsum panels. The thermal diffusivity is a function of the thermal conductivity and the temperature dependent specific heat capacity. As already mentioned, increase of the thermal conductivity will contribute towards increase of the heat-absorption rate; however, increase of the heat capacity will decrease the speed of heat absorption. When the PCM temperature is within the fusion temperature range, the ceiling panels have highest heat storage capacity, but lowest heat-absorption rate, which limits to some extend the rate of storage of the space sensible heat gains in the ceiling panels, and respectively the rate of increase of the space operative temperature.

By analyzing the effect of cooling load profile and intensity, it was shown the higher internal heat gains result in higher peak indoor operative temperatures, regardless of the higher amount of thermal energy stored in the ceiling panels. These results are attributed to the relatively slow heat absorption of the PCM-gypsum ceiling panels in comparison to the cooling load intensity. That is a limitation of the concept, showing that it cannot cope fast enough with space sensible heat gains with high rate of increase, which results in a faster increase of the operative temperature indoors.

As part of the parametric study, the passive and active PCM-gypsum ceiling panels' concepts were compared under similar (almost identical) space cooling loads. It was noticed that the rates of indoor operative temperature increase and the storage rate of thermal energy were identical for the office models with passive and active ceiling panels with identical space sensible heat gains. Better room temperature control in terms of maximum indoor operative temperatures was achieved by the passive panels' concept, which result was due to the night-time cooling principle. Discharging the ceiling panels with night-time ventilation results in lower space operative temperatures in the early morning hours (compared to local discharging of the active ceiling panels through the embedded pipes system), which helps to decrease the peak of operative temperature in the space during the day.

In terms of cooling load management, there are different advantages inherent in the passive and the active ceiling panels' concepts. When passive ceiling panels combined with night-time natural ventilation were used, the energy used for cooling was considered free (natural night-time ventilation. The obtained cooling demand reduction of 69%, due to energy stored in the ceiling panels, resulted in direct energy savings. Additionally, the peak cooling load was reduced by 70% which resulted in direct reduction of the maximum power capacity of the HVAC system.

The active ceiling panels' concept did not provide direct energy savings, due to the mechanical system needed for the embedded pipes night-time cooling. However, the peak power reduction of 32% would provide direct savings in terms of needed total HVAC system capacity. Additionally, the peak power reduction during occupancy hours was reduced by 64%. Furthermore, about 67% of the total daily cooling load was shifted to night-time hours, which brings benefits in terms of cost savings through utilization of time-of-use electricity tariffs.

9.3 Summary and discussion of Part IV

The objectives of the experimental study were to evaluate the performance, in terms of temperature control and cooling load management, of ceiling panels with PCM for a typical office environment. The PCM panels' system thermal performance was evaluated, through a series of experimental case studies, for different control strategies and operation principles, including active (night-time embedded pipes system) vs. passive (night ventilation) ceiling panels, and different internal loads intensity and cooling load pattern.

The ceiling panels used in the experimental study were built of micro-encapsulated paraffin material incorporated in a 25 mm thick clayboard with dimensions 125 cm x 62.5 cm. The experimental set-up was built in a climatic chamber built of internal and external steel sheets separated by 10 cm of insulation in the walls, roof and floor. This construction had a very low thermal mass, resulting in a very lightweight envelope. The indoor space was arranged as a typical office room and equipped with different heat gain simulators to represent occupants, equipment and solar heat gains. The chamber was equipped with a ventilation system and chilled water system to provide night-time cooling for the different case studies. Measurement equipment was installed to monitor different parameters of the HVAC system, the thermal environment and heat gains intensity in the space, as well as surface temperatures and heat flux of the PCM-clayboard ceiling panels.

The thermal performance of the PCM-clayboard ceiling panels was evaluated by six experimental case studies, three with active ceiling panels and three with passive panels. Different internal heat gains intensity were used in the different case studies.

In terms of cooling load management, the measurement results have showed that in the different experimental case studies up to 47% of the daily cooling loads were stored in the PCM-clayboard ceiling panels, and shifted to night time. Due to the fact that the night-time cooling in all experimental case studies was forced to operate in a continuous manner so as to discharge as good as possible the ceiling panels, and was not optimized for energy savings, no analysis on peak-load shaving and energy savings were done.

In terms of temperature control, the passive and active ceiling panels were an efficient solution for cooling loads of up to 232 Wh/m^2. Cooling loads with higher intensity could not be managed by the PCM-clayboard ceiling panels, due to limitation imposed by the speed of heat absorption of the ceiling panels. To fulfill the thermal comfort criterion for Category III from Standard EN 15251 (indoor operative temperature in the range 22 – 27°C) when higher cooling loads were present, higher rates of night-time cooling and additional supplementary cooling by the ventilation system during daytime should have been used in the chamber.

The results from some of the experiments have shown that in the morning hours, down to 1K lower temperatures than recommended comfort limit were measured. These low morning temperatures suggest the need of control over the minimum allowed indoor temperature during night-time cooling to prevent thermal discomfort due to too low temperatures during morning hours of occupancy. However, control over the night-time cooling may result in insufficient discharge of thermal energy stored in the PCM-clayboard ceiling panels, which will limit their storage capacity and alter their performance during the day.

The results from the experimental study were compared with results from computer simulations, in order to evaluate the capability of a computer simulation model to represent the behavior of PCM ceiling panels. Results for operative temperature, ceiling panels' surface temperature, surface heat flux, and stored thermal energy were compared. It was shown that the simulation models represent the actual situation in the climate chamber quite satisfactorily, with some minor differences encountered in the different case studies. These results give a positive indication about the findings of the parametric study presented in Part III of the thesis.

9.4 Conclusions

Within the limitations of this thesis and based on the findings from all parts and papers included in the thesis the following conclusions can be drawn:

Seasonal thermal energy storage in the ground

- Seasonal thermal energy storage of solar heat, utilizing underground storages, i.e. water tank, water-grave pit, borehole fields and aquifers, are technically feasible and work well;
- As part of central solar heating plants with seasonal storage, solar fractions of up to 57% of total delivered heat have been achieved;
- Construction costs of the seasonal storages are still too high;
- Thermal losses for water tank and water-gravel pit storage are relatively high;
- The high level of system complexity may alter significantly the efficiency and potential benefits;
- Underground thermal energy storage with ground-coupled (or ground-source) heat pumps for heating and cooling applications in buildings offers economic as well as environmental advantages in terms of energy savings and greenhouse gas emissions (through savings in primary fuel).
- Since the ground-coupled system functions both as a heat source and a heat sink, these double-effect storage projects may provide high energy savings (up to 77% in different projects).
- For ground-coupled heat pumps with borehole thermal energy storage, hybridization is a good approach towards reducing systems' investment cost. The hybrid equipment (boilers or cooling towers) preserves some of the energy efficiency of the system, but reduces the capital cost associated with the ground loop installation.

Building thermal mass utilization

- Thermally heavy buildings may reduce the diurnal temperature swings by 2-3K and reduce the daytime peak temperatures by 1-2K, in comparison to lightweight buildings.
- Depending on occupancy pattern and ventilation flowrate, compared to a lightweight building, a heavy building may increase the ability of the space to handle internal heat loads by more than 50%.
- In terms of energy savings, the high thermal mass may contribute significantly in the net cooling demand reduction of the building. Depending on HVAC system

control strategies and set points, and the occupancy pattern, compared to a lightweight building, a thermally heavy building may:

- Reduce the daytime cooling load by 18%
- Reduce the peak electricity use by 10-40%
- In the presence of time-of-use electricity tariffs, reduce the energy costs by 10-50%

- For buildings with TABS systems, reduction of the peak cooling demand of up to 50% may be achieved, compared to a system without storage effect like chilled ceiling panels.
- Depending on the hydronic circuit design, additional energy savings of 20-30% can be achieved.
- Optimized system control strategy may result in up to 50% reduction in the primary energy use.

PCM enhanced building thermal mass

- PCM-plasterboard offers significant benefits for thermal mass enhancement in lightweight buildings and retrofitting. However, in each case, a detailed cost-benefit analysis must be performed to justify the use such an expensive solution.
- PCMs with melting temperature range towards the lower boundary of the desired daily indoor temperature variation range were shown to be beneficial in terms of room temperature control.
- Selection of PCMs with optimum melting temperature may reduce the diurnal temperature swings by 1-2K and reduce the daytime peak temperatures by 1-3K, in comparison to PCMs with higher or lower melting temperatures than the optimum.
- The PCM melting temperature has also direct effect on the thermal energy storage capacity utilization of the added by the PCM thermal mass.
- Increase of the PCM-building material thermal conductivity has positive effect on their heat absorption rate. There is a tendency for increase of the benefit of higher thermal conductivity for space cooling loads with higher intensity.
- For passive PCM-gypsum and PCM-clayboard ceiling panels combined with night-time ventilative cooling energy savings of up to 70% and peak cooling load reduction by up to 70% were achieved.
- For thermally-activated PCM-gypsum and PCM-clayboard ceiling panels, peak power reduction of 32% was achieved. The cooling demand shifted from peak to

off peak hours was up to 67% of the total daily cooling load which may result in high cost savings if time-of-use electricity tariffs are utilized.

- A comparison between the computer simulations and experimental results show that the behavior predicted by the theoretical model fits well with the measurements.
- Regarding the night-time cooling principle used for regeneration of the thermal storage capacity of the PCM-gypsum and PCM-clayboard ceiling panels, the active cooling was more beneficial than the passive when high internal heat gains to the space were present, due to the local discharging of the stored thermal energy. For the lower range of internal heat gains studied in the thesis, there was similar performance of the cooling principles.
- A limitation of the concept of PCM-enhanced thermal mass is that the PCM-building material composite is characterized with slow heat absorption rate, which makes it inappropriate for use in buildings with space sensible heat gains with high rate of increase.

9.5 Suggestions for future work on PCM enhanced thermal mass

The work done in the thesis includes literature review and analytical and experimental evaluation of different thermal energy storage concept. The main objectives of using the storage systems investigated are to provide energy and cost efficient means for coping with the mismatch between thermal energy availability and demand. The inherent benefits of these systems should result in energy savings by reduction of the primary energy used and by thermal load leveling and peak demand reduction.

Thermal energy storage systems have often been applied in buildings with the objective to demonstrate that the energy storage techniques could be successfully applied rather than to optimize the building performance. Indeed the design of the building and the design of the energy storage were often not coordinated and energy storage simply supplied part or whole of the building demand whatever it might be. The future research should be oriented towards developing integrated design techniques which will result in coordinated set of actions for improved building's and thermal energy storage concept's design. Utilization of the maximum potential benefits of the different thermal energy storage systems requires that the concepts are intimately integrated into sustainable building design.

In addition, the different technologies have shown different deficiencies that obstruct their wide application:

- The seasonal storage technologies considered in the thesis require further investigations in order to make them economically competitive with conventional energy sources. Research could include studies related to cost reductions for construction of the storage, which expense was identified as the main economical barrier.
- For TABS systems some of the main challenges that require further investigation are the hydronic system design, and the control of operation of these systems.
- For the PCM ceiling panels investigated in the thesis, the main drawbacks identified have been the high cost of microencapsulated PCM and the low heat absorption rate. Studies on cost reduction would increase the acceptance of this technology. The heat absorption rate increase can be achieved by the use of high conductive materials, like graphite, which could be an area of further research. Last, but not least, control over the night-time cooling, for discharging the stored in the PCM thermal energy, for improved temperature control capabilities and reduce energy use can be an area for investigation.

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Symbols and Abbreviations

TES	Thermal energy storage
BTES	Borehole thermal energy storage
ATES	Aquifer thermal energy storage
PCM	Phase change material
TABS	Thermo-active building system
HVAC	Heating, ventilation and air-conditioning
MFR	Mass-to-floor ration
TRNSYS	TRaNsient SYstem Simulation Program
IWEC	International weather for energy calculations
EN	European Norm
ISO	International Organization for Standardization
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers

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Appendix A – List of Papers

Most relevant papers:

Paper I *"Thermal Energy Storage – A review of concepts and systems for heating and cooling applications in buildings: Part I – Seasonal storage in the ground."* Published in HVAC&R Research Journal, Issue Nr. 18, Part 3, pp. 515-538.

Paper II *"Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels."* Accepted Manuscript in Energy & Buildings Journal (2014).

Paper III "*Use of PCM-Plasterboard Ceiling Panels for Building Thermal Mass Enhancement, Temperature Control and Peak Load Management in a Continental Mediterranean Climate"*. Paper presented at CLIMA 2013 Conference. 16-19 June 2013, Prague, Czech Republic.

Papers with less relevance, or Conference papers used for the basis for creating Journal papers:

Paper IV "*Simulation and optimisation of a ground source heat pump with different ground heat exchanger configurations for a single-family residential house"*. Paper presented at Healthy Buildings 2012 Conference, 8-12 July 2012, Brisbane, Australia.

Paper V *"Ground source heat pump combined with thermo-active building system with incorporated PCM for low-energy residential house"*. Paper presented at INNOSTOCK 2012 Conference, 16-18 May, Lleida, Spain.

Paper VI *"Building Thermal Energy Storage – Concepts and Applications"*. Paper presented at RoomVent 2011 Conference, 19-22 June, Trondheim, Norway.

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Thermal energy storage—A review of concepts and systems for heating and cooling applications in buildings: Part 1—Seasonal storage in the ground

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Thermal energy storage—A review of concepts and systems for heating and cooling applications in buildings: Part 1—Seasonal storage in the ground

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The use of thermal energy storage (TES) in buildings in combination with space heating and/or space cooling has recently received much attention. A variety of TES techniques have developed over the past decades. TES systems can provide short-term storage for peak-load shaving as well as long-term (seasonal) storage for the introduction of natural and renewable energy sources. TES systems for heating or cooling are utilized in applications where there is a time mismatch between the demand and the most economically favorable supply of energy. The selection of a TES system mainly depends on the storage period required, economic viability, and operating conditions. One of the main issues impeding the utilization of the full potential of natural and renewable energy sources, e.g., solar and geothermal, for space heating and space cooling applications is the development of economically competitive and reliable means for seasonal storage of thermal energy. This is particularly true at locations where seasonal variations of solar radiation are significant and/or in climates where seasonally varying space heating and cooling loads dominate energy consumption. This article conducts a literature review of different seasonal thermal energy storage concepts in the ground. The aim is to provide the basis for development of new intelligent TES possibilities in buildings.

Introduction

Energy demand in buildings varies on a daily, weekly, and seasonal basis. This demand can be matched with the help of thermal energy storage (TES) systems that operate synergistically and are carefully matched to each specific application. TES systems have the potential of making the use of HVAC systems more effective, and they are an important means of offsetting the mismatch between thermal energy availability and demand. Well-designed systems can reduce initial and maintenance costs and improve energy efficiency (Dincer and Dost, 1996; Dincer et al. 1997).

A variety of TES techniques for heating and cooling applications have been developed over the past decades (Dincer and Rosen 2011). It is favorable to characterize the different types of TES depending on the storage duration: *short-term* (*diurnal*) storage or *long-term* (*seasonal*) storage. Nordell (2000) specified additional parameters for classification of TES systems, according to

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storage purpose (heating and/or cooling), *storage temperature* (low <40–50°C [~100–120°F] or high >50°C [~120°F]), *storage technology* (borehole TES [BTES], pit-tank TES, phase change materials [PCMs], etc.), and *storage application* (residential or commercial). The different storage concepts have very different characteristics, possible applications, strengths, and weaknesses. The selection of a TES system mainly depends on the storage period required, economic viability, and operating conditions.

In continental climates, it is possible to store heat from the warm summer months for use in winter, while the cold ambient temperatures of winter can charge a cold store to provide cooling in summer. This example of seasonal storage can meet the energy needs caused by seasonal fluctuations in temperature.

Due to the intermittent nature of the energy source, achieving the full potential of solar thermal technologies, for space heating and domestic hot water (DHW) applications, is dependent on the availability of efficient and effective energy storage systems. This is particularly true at high latitude locations, where seasonal variations of solar radiation are significant, and in cold climates, where seasonally varying space heating loads dominate energy consumption.

This literature review article attempts to summarize developments during the last four decades in seasonal TES in the ground, using different storage concepts and utilizing different natural and renewable energy sources. The aim is to provide the basis for development of new intelligent seasonal TES possibilities for use in combination with space heating, space cooling, and DHW applications.

Underground TES (UTES) concepts

The principle methods available for seasonal storage of thermal energy mostly store energy in the form of sensible heat. Storage of sensible heat is influenced by energy losses during the storage time. These losses are function of storage time, storage temperature, storage volume, storage geometry, and thermal properties of the storage medium. Since seasonal TES requires large inexpensive storage volumes, due to the large storage timescales, the most promising technologies were found in the ground, where the ground temperatures vary much less than the ambient temperature. Such systems are called UTES systems (Nordell 2000). Among the UTES systems developed since the 1970s, the ongoing engineering research focused mainly on four types of storages: water tank, gravel-water pit, aquifer TES (ATES), and BTES; see Figure 1. In Table 1, are summarized the characteristics of the main underground seasonal storage concepts.

Water-tank TES usually consists of a reinforced concrete tank partially or fully buried in the ground, which can be built nearly independently of geological conditions. It is thermally insulated at least on the roof area and on the vertical walls. Furthermore, steel liners are introduced in the structure to guarantee water tightness and to reduce thermal losses caused by vapor transport through the walls (Schmidt et al. 2004). Due to the high specific heat of water, and the possibility for high capacity rates for charging and discharging, this technology seems to be the most favorable from a thermodynamic point of view.

Gravel-water pits consist of a mix of gravel and water and are normally buried in the ground. They need to be waterproofed and insulated on at least at the side walls and on the top (Schmidt et al. 2004). Thermal energy is charged into and discharged out of the storage either by direct water exchange or by a heat exchanger based on plastic piping installed in different layers inside the storage. The gravel-water mixture has lower specific heat capacity than water alone, and for this reason, the volume of the whole basin has to be higher compared to water-tank storage to obtain the same thermal storage capacity.

Aquifers are below-ground widely distributed sand, gravel, sandstone, or limestone layers with high hydraulic conductivity that are filled with groundwater (Schmidt et al. 2004). If there are impervious layers above and below, and no or low natural groundwater flow, they can be used for thermal storage. In this case, two wells or groups of wells are drilled into the aquifer and serve for extraction or injection of groundwater. During charging periods, cold groundwater is extracted from the cold well, heated up by the heat source, and injected into the hot well. In discharging periods, the flow direction is reversed: warm water is extracted from the warm well, cooled down by the heat sink and injected into the cold well. Due to the different flow directions, both wells are equipped with pumps and production and injection pipes. Because the storage volume of ATES cannot be thermally

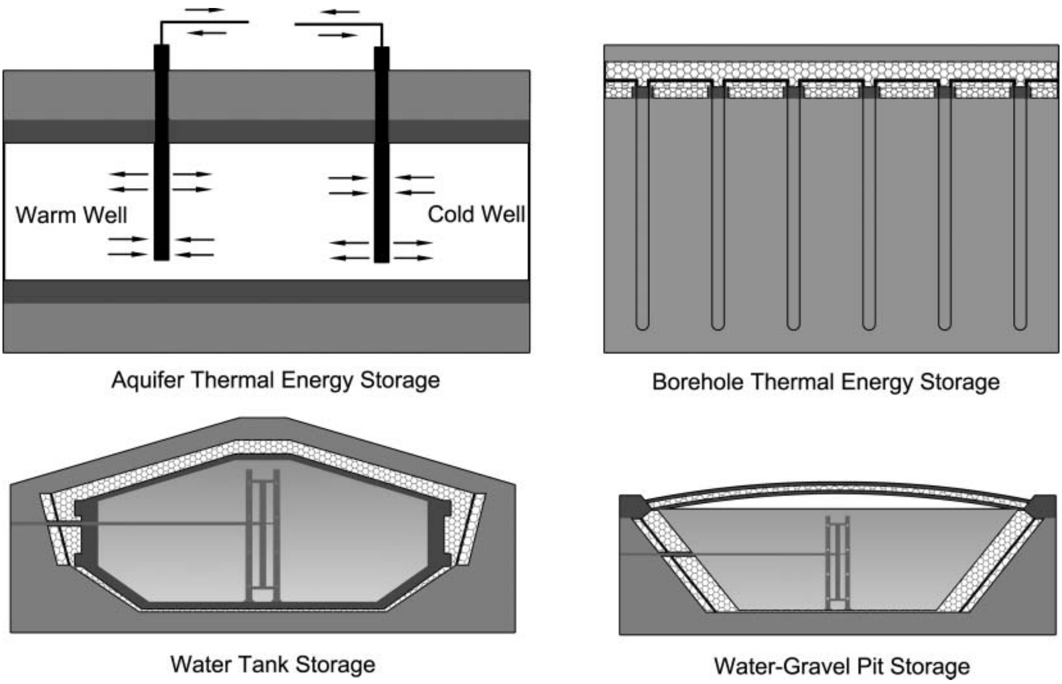

Figure 1. UTES concepts.

insulated against the surroundings, heat storage at high temperatures (above 50°C [122°F]) is normally only efficient for large storage volumes (more than 20,000 m^3 [706,300 ft^3]) with a favorable surface-to-volume ratio. For low-temperature or cooling applications also, smaller storage can be feasible. Especially for high-temperature thermal storage, a good knowledge of the mineralogy, geochemistry, and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling, etc.

In BTES, thermal energy is directly stored in the ground. In suitable geological formations (e.g., rock- or water-saturated soils [Schmidt et al. 2004)], U-pipes, or so-called ground heat exchangers, are inserted into vertical boreholes to a depth of 30–200 m (98–656 ft) to build a huge heat exchanger. The boreholes are usually filled with groundwater (Northern Europe), or with bentonite, quartz sand, or thermally enhanced grouts (North America, Central Europe). While water is running in the U-pipes, heat can be fed into or out of the ground. The heated ground volume comprises the volume of the storage. At the top of the storage, there is usually a heat insulation layer to reduce thermal losses to the surface.

Depending on the application and the heating/cooling demand on the storage, different design requirements for borehole configuration and groundwater flow may apply. For solar thermal applications, due to the need for seasonal storage of solar heat, minimized heat exchange between the BTES and surrounding ground is desired. Therefore, rectangular or circular configuration (with high volume-to-surface area ratio) of the storage and low natural groundwater flow are prerequisites for design. For ground-source heat pump (GSHP) applications, the requirements for the configuration of the boreholes are set by the share of the heating and cooling of the total energy need of the building. For example, if there is a cooling-dominated situation, the heat rejection to the ground in summertime will be higher than the heat extraction from the ground in winter. Due to that imbalance in the ground loop, the ground temperature will increase. The increasing of the ground temperature will reduce the efficiency of the GSHP system in the summer. The opposite situation will be observed in a heating-dominated situation. In these cases, the heat exchange area between the borehole system and surrounding ground should be maximized in order to avoid heat accumulation or depression in the borehole field. That would make the linear borehole configuration more beneficial. Additionally, high groundwater flow would enhance the dissipation of thermal energy

Table 1. Comparison of storage concepts (Schmidt et al. 2003, Novo et al. 2010).

Storage concept	Water tank	Gravel–water pit	Aquifer	Borehole
Storage medium	Water	Gravel–water	Sand/water–gravel	Soil/rock
Thermal capacity, kWh/m^3 (kBtu/ft^3)	60–80 (5.8–7.73)	30–50 (2.9–4.83)	30–40 (2.9–3.9)	15–30 (1.45–3.9)
Storage volume for 1 m^3 (35.3 ft^3) water equivalent	1 m^3 (35.3 ft^3)	1.3–2 m^3 (46–71 ft^3)	2–3 m^3 (71–106 ft^3)	3–5 m^3 (106–177 ft^3)
Geological requirements	- Stable ground conditions	- Stable ground conditions	- Natural aquifer layer, high hydraulic conductivity	- Drillable ground
	- Preferably no ground water	- Preferably no ground water	- Confining layers on top and below	- High heat capacity
	- 5–15 m (16–49 ft) deep	- 5–15 m (16–49 ft) deep	- No or low natural ground water flow	- High thermal conductivity
			- Suitable water chemistry at high temperatures	- Low hydraulic conductivity
			- 20–50 m (65–164 ft) deep	- No or low natural ground water flow (<20 m/year [65 ft/year])[a]
				- 30–200 m (98–656 ft) deep
Application	Heating: CSHPSS	Heating: CSHPSS	Heating: CSHPSS Heating and cooling: GSHP	Heating: CSHPSS[a] Heating and cooling: GSHP

[a]Geological requirement for seasonal storage of solar thermal energy.

in the surrounding ground, thus improving system performance. For balanced annual heating and cooling loads, the GSHP-BTES system would benefit from using the ground system for seasonal storage of heat or cold, and the design prerequisites for a solar thermal system will apply.

BTES has a horizontal rather than vertical temperature stratification from the center to the borders. This is because the heat transfer is driven by heat conduction and not by convection. At the boundaries, there is a temperature decrease as a result of the heat losses to the surroundings. When rectangular or circular storage is designed, the horizontal stratification is supported by connecting the supply pipes in the center of the storage and the return pipes at the boundaries. During charging, the flow direction is from the center to the boundaries of the storage to obtain high temperatures in the center and lower ones at the boundaries of the storage. During discharging, the flow direction is reversed.

One advantage of this type of storage is the possibility for a modular design. Additional boreholes can be connected easily, and the store can grow, e.g., with the size of a housing district. The size of the storage should be three to five times higher than that of water-tank storage to obtain the same thermal capacity. Table 2 shows typical general values for BTES systems.

The interest in large-scale seasonal TES started with the oil crisis in the early 1970s. The objectives of such systems are either to store solar heat collected in summer for space heating in winter, or to provide heating and cooling by storing heat underground in summer and removing heat in winter.

Table 2. Typical values of BTES systems for heat storage applications.

Borehole diameter	0.1–0.15 m (0.3–0.5 ft)	Flowrate in U-pipes	0.5–1.0 m/s (1.6–3.3 ft/s)
Borehole depth	30–200 m (98–656 ft)	Average capacity per m (ft) borehole	20–30W/m (Btu/h.ft)
Distance b/n boreholes	2–4 m (6.6–13.1 ft)	Minimum/maximum inlet temperature	–5/+90°C (23–194°F)
Ground thermal cond.	2–4 W/(mK) (3–7 Btu/(h.ft.°F))	Cost of BTES per m (ft) borehole	50–80 €/m (20–33 US $/ft)

Source: http://www.highcombi.eu

In winter, a GSHP extracts heat from the thermal storage; in summer, it extracts heat from the building to store it in the ground. These systems contribute significantly to improving the energy efficiency and reducing the greenhouse gas emissions to the atmosphere.

Design guidelines for UTES

For the construction of ground-buried TES, like water tanks and gravel-water pit storages, there are no standard procedures available regarding wall construction, charging device, geometry (e.g., surface-to-volume ratio), etc. Due to the size and geometry, and also due to the requirements in terms of leakage detection and lifetime, most techniques and materials have their origin in landfill construction. However, with respect to high operation temperature, materials and techniques cannot be simply transferred. Design recommendations for construction of water-tank and gravel-water pit storages are given in the HIGH-COMBI Report (2008).

General demands and recommendations for the design of ATES and BTES systems can be found in the Verein Deutscher Ingenieure's (VDI [Association of German Engineers] n.d.) "Guideline VDI 4640: Thermal use of the Underground, Parts 1–4." The guidelines concern the thermal use of ground to a depth of about 400 m (1300 ft). Systems for heating only, cooling only, and both heating and cooling are treated in Part 1. Environmental aspects, such as primary energy use, CO_2 emissions, thermal impacts on the ground and groundwater, hydraulic impacts, and possible consequences of leakage of heat carrier fluids, are included as well. Part 2 includes design guidelines for the possible specific heat extraction rate for ground-coupled heat pumps with vertical boreholes or shallow horizontal pipes. In Part 3, storage-specific aspects, e.g., water treatment methods to prevent precipitation caused by chemical changes and suitable materials for different applications (temperatures), are mentioned. ATES and BTES systems are described in detail, including hydrogeological prerequisites and recommendations for design. Part 4 focuses on the direct usage of underground cold or heat without any additional equipment, such as groundwater cooling or heating.

Additional information for ground-source cooling systems with TES, utilizing ATES and BTES concepts, is given in a pre-design guide developed by Hummelshøj (2004).

Seasonal storage of solar thermal energy for heating applications

Seasonal heat storage for solar thermal applications needs large volumes of storage to supply the energy stored during summertime for winter. That large storage requires the development of technologies capable of minimizing heat losses in order to preserve the thermal performance and lifetime of the solar heating plant. These approaches must be coupled with low investment, at least lower than conventional heating and cooling systems.

Four different seasonal heat storage types for solar thermal applications have been investigated in this article: gravel-water storage, gravel-water pit storage, BTES, and ATES. The selection of a specific storage type depends on the geological and geo-hydrological situation in the ground at the respective construction site. A preliminary geological examination of the site is recommended, especially for ATES and BTES. Determining the geological and geo-hydrological conditions can be expensive and time consuming. Ford and Wong (2010) studied the above-mentioned phenomena and presented regional models for screening potential underground areas for ATES and BTES systems implementation. The findings are based both on geological data

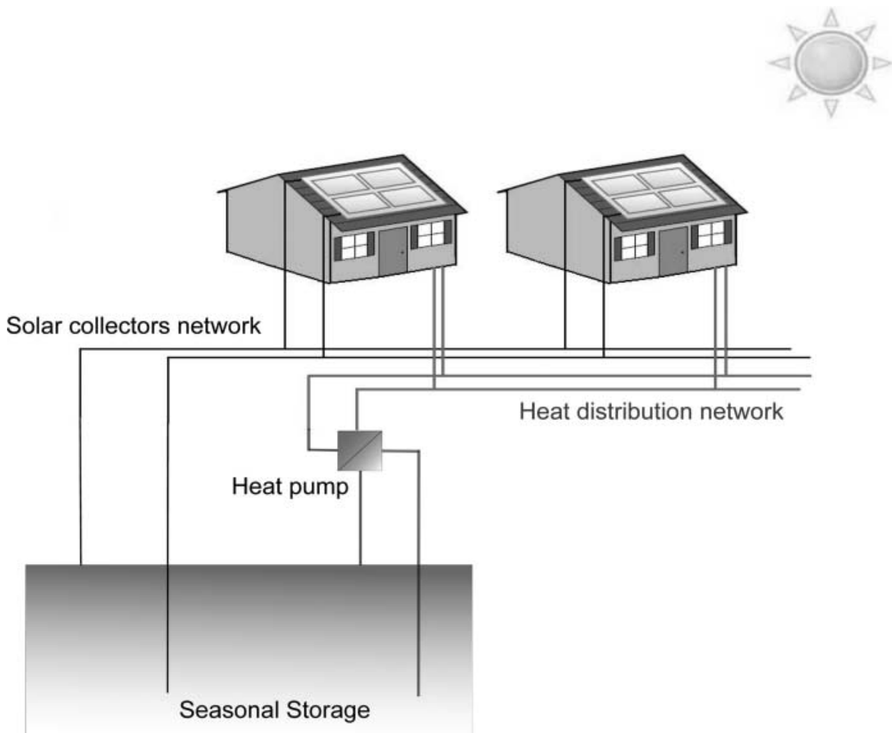

Figure 2. Scheme of a central solar heating plant with seasonal storage.

and output from a three-dimensional groundwater flow model, MODFLOW (McDonald and Harbaugh 1988).

Seasonal storage of solar thermal energy for space heating purposes has been under investigation in Europe since the mid 1970s within large-scale solar heating projects. Most large-scale solar systems have been built in Sweden, Denmark, The Netherlands, Germany, and Austria (Dalenbäck 2007). The first demonstration plants were developed in Sweden in 1978/1979, based on results from a national research program (Dalenbäck and Jilar 1985). The seasonal storage concept research work continued within the IEA "Solar Heating and Cooling" program. Experiences have been gained and exchanged in Task VII's central solar heating plants with seasonal storage (CSHPSS) since 1979 in many countries. In the past two decades, the main activities have been within the work initiated in the CSHPSS Working Group, IEA Solar Heating and Cooling program, the work carried out in Europe within the EU/APAS-project "Large-Scale Solar Heating Systems" (Fisch et al. 1998), as well as the German R&D programs Solarthermie-2000 and Solarthermie-2000plus (Lottner et al. 2000; Schmidt et al. 2004; Bauer et al. 2010). Figure 2 shows a scheme of a CSHPSS (distributed rooftop solar collectors, central plant with heat pump, solar collectors, and heat distribution networks).

So far, the development of seasonal storage has been aimed at heating large district system stores part of CSHPSS in order to fulfill technical viability and cost effectiveness by using large storage volumes. Fisch et al. (1998) reviewed large-scale solar plant development in Europe during the 1990s. The work refers to two large-scale solar heating applications: systems with short-term (diurnal) storage designed to supply 10–20% of the annual heating demand or 50% of the DHW, and systems with long-term (seasonal) storage capable of supplying 50–70% of the annual heating demand. Within the findings of that work was that large-scale solar applications benefit from the effect of scale. Compared to small solar DHW systems, the solar heat cost can be cut at least in third. Among the main results of the evaluation of the existing projects was the need to reduce the cost-benefit ratio for CSHPSS.

Comparison of technologies and experiences from pilot projects for CSHPSS

Table 3 summarizes the technical characteristics of some demonstration plants in central solar heating systems with water tank, gravel-water pit, borehole, and aquifer storage. The experimental projects have been selected as they are large-scale pilot plants. An overview of the effectiveness of diverse configurations of these systems, including solar heat systems costs, is provided. The given numbers for the solar fraction of total heat delivered are simulated values for long-term operation. Depending on the type of seasonal heat store, the systems have start-up times of three to five years to reach normal operating conditions. Within this time, the underground around the seasonal storage has to be heated up, and hence, heat losses are higher than in the long-time operation. Because of this, the system efficiency is lower in the first years of plant operation (Schmidt et al. 2004).

Water-tank TES

Water-tank TES is technically feasible and works well. However, construction costs and thermal losses are still too high. Experiences from the plants built in Hamburg and Friedrichshafen have shown that the main cost for hot water storage tanks is caused by the concrete construction, ground works, insulation, and the use of steel liners to reduce water permeability (Kübler et al. 1997). Considerable cost reductions can be obtained with the development of high-density concrete materials, which would allow the omission of the use of expensive steel liners for the storage construction (Schmidt et al. 2004). The water-tank storage in Hannover is the first one utilizing that concept on a large scale. Another novelty in that project has been the introduction of stratification devices in the water-tank storage. Problems with high thermal losses due to wet thermal insulation have been experienced in Sweden in the past (Dalenbäck and Jilar 1985), and they have revealed the importance of water-tank insulation for the long-term performance of CSHPSS. Advances in stratification devices and heat insulation have resulted in significantly lower construction costs for the seasonal storage in Munich than for costs experienced in previous projects (Schmidt and Mangold 2006). Further research and development related to high-density concrete materials, prefabricated sandwich elements for water-tank wall construction, and simultaneous charging and discharging stratification devices would give the possibility of improving the thermal performance and decreasing the construction costs for water-tank seasonal storage technology.

Gravel-water pit TES

Experiences with gravel-water storage in Chemnitz have shown that sealing of the pit, insulation, and ground works account for a significant part of the costs (Schmidt et al. 2004). The seasonal storages in Steinfurt (Pfiel and Koch 2000) and Ottrupgaard (Heller 2000) have shown that the construction of the wall (liner, insulation) can barely be realized at the required low costs to be cost effective for seasonal storage. Moisture protection of the insulation is also important for the concept. In addition, the seasonal gravel-water pit storage in Ottrupgaard has shown difficulties in making it sufficiently tight and localizing and repairing leakages. The concept of a floating cover was investigated for the plants in Ottrupgaard and Eggenstein (Bauer et al. 2010), and it appears to be an expensive construction. Research for developing cost-effective solutions is needed. Further studies regarding system thermal performance relative to the use of direct and indirect heat exchangers are necessary.

BTES

For BTES, the experiences with CSHPSS built in Neckarsulm (Nußbicker et al. 2003; Bauer et al. 2010), Crailsheim (Mangold 2007), and Anneberg (Nordell and Hellstrom 2000; Lundh and Dalenbäck 2008) show that the major investment for a solar plant is the cost of building the storage, e.g., drilling boreholes, constructing heat exchangers, refilling boreholes. As drilling costs increase with the depth of the borehole, the length and the number of boreholes are important. Thermal properties (heat capacity, thermal conductivity) of the ground determine the spacing of the heat exchangers. Number, length, and spacing of boreholes taken together allow the storage volume to be calculated. In addition to storage design, due to the low heat transfer rates between the circulating fluid and ground, these systems have shown dependence on the development of buffer storage techniques. Buffer storage hot water tanks are often added to the system in order to manage the high-capacity rates of the solar collectors during summertime and the high-demand rates for heating and DHW during wintertime.

Table 3. Technical data of CSHPSS.

CSHPSS with storage type	Total heat demand, GJ/a (GBtu/a)	Solar collector area, m^2 (ft^2)	Storage volume, m^3 (ft^3)	Solar fraction, %	Maximum design storage temperature, °C (°F)	Solar heat cost analysis date, MWh (3.41 * MBtu)	References
Water tank							
Hamburg, DE	5796 (5.5)	3000 (32, 291)	4500 (159* 10^3)	49[a]	95 (203)	256 EUR	Kübler et al. (1997), Schmidt et al. (2004), Lottner (2000), Bauer (2010)
Friedricshafen, DE	14, 782 (14)	5600 (60, 277)	12, 000 (424* 10^3)	47[a]	95 (203)	158 EUR	Kübler et al. (1997), Schmidt et al. (2004), Lottner (2000), Bauer (2010)
Hannover, DE	2498 (2.4)	1350 (14, 531)	2750 (97* 10^3)	39[a]	95 (203)	414 EUR	Schmidt et al. (2004), Lottner (2000), Bauer (2010)
Munich, DE	8280 (7.9)	2900 (31, 215)	5700 (201* 10^3)	47[a]	95 (203)	240 EUR	Schmidt and Mangold (2006), Bauer (2010)
Ingelstad, SE		1320 (14, 208)	5000 (177* 10^3)	14[a]		1900 SEK	Dalenbäck et al. (1985)
Lambohov, SE		2700 (29, 062)	10, 000 (353* 10^3)	37[a]		1100 SEK	Dalenbäck et al. (1985)
Hoerby, DK			500 (18* 10^3)				Heller (2000)
Herlev, DK	4520 (4.3)	1025 (11, 033)	3000 (106* 10^3)	35[a]			Heller (2000)
Gravel–water pit							
Stuttgart, DE	360 (0.34)	211 (2271)	1050 (37* 10^3)	60[a]	85 (185)		Hahne 2000
Chemnitz, DE	4320 (4.1)	2000 (21, 527)	8000 (283* 10^3)	42[a]	85 (185)	240 EUR	Schmidt et al. (2004)
Steinfurt, DE	1170 (1.1)	510 (5489)	1500 (53* 10^3)	34[a]	90 (194)	424 EUR	Pfiel et al. (2000)
Eggenstein, DE	3276 (3.1)	1600 (17, 222)	4500 (159* 10^3)	40[a]	80 (176)		Bauer et al. (2010)
Ottrupgaard, DK	1630 (1.55)	560 (6027)	1500 (53* 10^3)	16[a]			Heller (2000)

BTES							
Neckarsulm, DE	1663 (1.58)	5000 (53, 819)	63, 400 ($2240^{*}\ 10^{3}$)	50^{a}	85 (185)	172 EUR	Nußbicker et al. (2003), Schmidt et al. (2004), Bauer et al. (2010)
Crailsheim, DE	14, 760 (14)	7300 (78, 576)	37, 500 ($1324^{*}\ 10^{3}$)	50^{a}	85 (185)	190 EUR	Mangold (2007)
Attenkirchen, DE	1753 (1.7)	800 (8611)	10, 000 ($353^{*}\ 10^{3}$)	55^{a}	85 (185)	170 EUR	Schmidt et al. (2004)
Anneberg, SE	3888 (3.7)	3000 (32, 291)	60000 ($2120^{*}\ 10^{3}$)	60^{a}	45 (113)	1000 SEK	Nordell et al. (2000), Lundh et al. (2008)
Okotoks, CA	1900 (1.8)	2293 (24, 681)	35, 000 ($1236^{*}\ 10^{3}$)	90^{a}	80 (176)		McDowell & Thornton (2008), Sibbit et al. (2007), Chapuis & Bernier (2009)
ATES							
Rostock, DE	1789 (1.7)	1000 (10, 763)	20, 000 ($706^{*}\ 10^{3}$)	62^{a}	50 (122)	255 EUR	Schmidt et al. (2000, 2004), Lottner (2000), Bauer (2010)

Note: CA = Canada, DE = Germany, DK = Denmark, SE = Sweden.
[a]Calculated values for long-time operation; simulations carried out using TRNSYS dynamic simulation software; weather data of the test reference year (TRY) used in the simulations.

ATES

Well construction is the predominant part of the costs for ATES. In reality, depending on site-specific conditions, several serious problems have to be solved, e.g., clogging of wells, scaling of the external heat exchangers, necessity of water treatment, and high heat losses, especially in small aquifer storage projects like the one in Rostock (Lottner et al. 2000; Schmidt et al. 2004; Bauer et al. 2010).

Operational experiences and design considerations for CSHPSS

The operational characteristics of the different CSHPSS considered in this review article are based on simulated values for long-term performance of the solar plants. In Bauer et al. (2010), three different types of seasonal TES have been tested and monitored under realistic operating conditions: Friedrichshafen (water tank), Neckarsulm (boreholes), and Rostock (aquifer). Their operational characteristics are compared using measured data from an extensive monitoring program. The long-term operational experiences are shown.

The solar fraction based on total heat demand for the plant in Friedrichshafen for the period 1997–2007 varied between 21% and 33%, where the design value has been 47%. One reason the targeted value was not met was that the heat demand for the buildings was 10% higher than expected, due to the increased living area compared to initial design. As a result, the additional heat demand was covered by the two gas condensing boilers installed in the system, which decreased the demand covered by solar energy. In addition, the design return temperatures of the heat distribution network have been assumed to be lower (40°C [104°F] yearly average weighted by volumetric flow) than measured values of up to 55.4°C (132°F) in 2006. The reason for the high return temperatures of the heat distribution network has been poorly performing heat exchangers at the demand (buildings) side. Because of the high net return temperatures, the TES has been operating at higher than design temperatures, which has resulted in increased heat losses of the thermal storage between 322 MWh/a and 482 MWh/a (1100 MBtu/a and 1646 MBtu/a), in contrast to design values of 220 MWh/a (751 MBtu/a). The higher operating temperature of the thermal storage has also caused higher temperatures in the solar collector circuit and thus reduced collector efficiency.

The CSHPSS in Neckarsulm has been monitored in the period 1999–2007. The solar fractions achieved (based on total heat demand) have been between 17% and 44.8%, where the design value has been 50%. Reasons for not achieving the desired solar fractions have been the 10% smaller-than-designed solar collectors' area and the higher net return temperatures of the heat distribution net (47°C–50°C [116°F–122°F] instead of 40°C [104°F]). In addition, the highest achieved solar fraction of 44.8% has been obtained during the last year of monitoring, when the maximum borehole seasonal storage temperature reached 65°C (149°F), 20°C (68°F) lower than planned. The smaller solar collector area and the heat up of the surrounding ground have contributed to that effect.

Monitoring results from the solar heating plant with aquifer seasonal storage in Rostock have shown solar fractions from 32% to 57%. The maximum temperature of the storage has been limited to 50°C (122°F) due to local hydrogeological conditions. The heat distribution net has been operating at 45/30°C (113/86°F) supply/return temperatures, which required the use of a heat pump for utilization of the stored heat. Due to the use of the heat pump and the high efficiency of the aquifer storage, the system has managed to reach the high solar fraction values.

The results from the monitoring campaigns at the different solar plants have shown that in order to achieve high solar energy efficiency, the solar plants have to be operated at low temperatures. Low storage temperature limits heat losses and improves solar collector efficiencies. Suitable techniques for fully benefitting from such low-temperature systems are to use low-temperature heating systems (typical range of 25°C–35°C [77°F–95°F]), like floor and wall heating in the buildings. In contrast, high-temperature systems must be built on a much bigger scale than low-temperature systems because of the higher storage heat losses.

For seasonal storage, low-temperature concepts with the use of heat pumps to raise the temperature of the water used for space heating to a suitable level is an appropriate option. This technology, conceptually and practically implemented in the plants in Rostock, Eggenstein, and Crailsheim (Lottner et al. 2000; Schmidt et al. 2004; Bauer et al. 2010), and in conceptual phase for the plant in Okotoks (Chapuis and Bernier 2009), enables the utilization of the full potential of solar heating plants with seasonal storage. Using a heat pump to discharge the seasonal storage to lower temperatures allows higher usability and increased storage capacity and storage efficiency. The solar plant becomes more robust against high return temperatures of the heat distribution net and solar collectors net, which allows reduction of the solar collector area required, increase of the solar collectors' efficiency, and obtaining high solar fractions (based on total heating demand).

The solar fraction of the delivered heat is not the only parameter that can be used for performance assessment of CSHPSS. In addition, the efficiency of solar-assisted district heating systems can be evaluated by the amount of solar heat per m^2 collector area delivered into the district heating net. Even though this parameter is dependent on local site conditions, like irradiation on the collector pane, it could give insight into any advantages or disadvantages of using different storage concepts. The monitoring results from the different plants shown in Bauer et al. (2010) do not show any clear tendencies in favor of or against a certain storage concept.

In addition, the above-discussed parameter could give some design prerequisites regarding solar collector area and storage volume. Different methods for determining the optimal size of collector area and storage volume for seasonal storage of solar heat have been developed. Braun et al. (1981) described a methodology for the design of these systems using the simulation program TRNSYS (Klein 2004). Significant reduction in the collector area has been achieved by use of seasonal storage. This effect is more pronounced for higher solar fractions. It has been shown that the trade-offs between collector area and storage volume requirements for a fixed system performance are location dependent. Greater reductions in collector area requirements with increasing storage capacity occur in northern latitudes (valid for the northern hemisphere). Similar results have been confirmed from the demonstration plants studied by Lottner et al. (2000), Schmidt et al. (2004), and Bauer et al. (2010). However, no clear guidelines or design recommendations have been developed.

The seasonal energy storage technologies for solar energy applications are characterized by many factors, such as solar collectors, annual sun exposure, heat distribution networks, heat demand and insulation of the buildings, and the seasonal thermal storage requirements. Once these technologies have been well developed, the main effort consists of reducing costs in order to make them market competitive against conventional energy sources.

As some authors suggest, the specific storage costs are related to water-equivalent storage volume. The water equivalent is the corresponding water volume to store the same amount of heat. Experiences carried out in demonstration plants have achieved cost reduction by increasing the storage volume in large-scale solar applications. Figure 3 presents the cost data of some pilot and demonstration plants reviewed in this study. The strong cost reduction with an increasing storage volume is obvious. Appropriate sizes for seasonal heat storage are located between 2,000–20,000 m^3 (70,600–706,000 ft^3) water

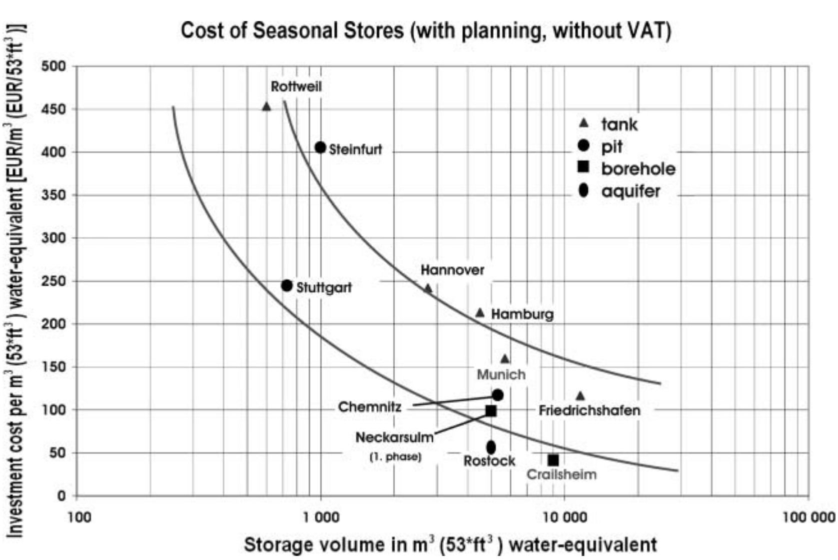

Figure 3. Cost of seasonal stores for CSHPSS (Lottner et al. 2000; Schmidt et al. 2004; Mangold 2007).

equivalent. Within this range, the investment costs vary between 40–250 €/m^3 (1.50–9.30 US \$/ft^3). Generally, water-tank storage is the most expensive concept. On the other hand, it has some advantages concerning the thermodynamic behavior and it can be built almost independently of the geohydrological site conditions. The lowest costs can be reached with ATES and BTES. However, they often need additional equipment for operation, such as buffer storage or water treatment, and they have the highest requirements on the local ground conditions.

The economy of CSHPSS depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Before starting the design of a new plant, geological conditions of the location, characteristics of the heat source, and demands of the consumers have to be analyzed thoroughly. Important parameters are maximum and minimum operating temperatures of the storage and heat distribution system. Optimal size of solar collector area and seasonal storage volume are of vital importance.

To determine the economy of a type of storage, the investment and maintenance costs of that storage have to be related to its thermal performance (the cost of the usable stored energy). If the geohydrological site conditions make different storage types feasible, an economic optimization via system simulations should be conducted by taking the construction costs of the different concepts into account.

The first attempts to develop dynamic simulation tools capable of determining the technical feasibility and cost effectiveness of CSHPSS were performed in Task VII's "CSHPSS" of the IEA "Solar Heating and Cooling" program (Chant et al. 1983). The applicability and the limitations of the computer simulation programs MINSUN (Mazzarella 1990) and TRNSYS (Klein 2004) in simulating a wide range of CSHPSS with different collector types, different seasonal storage types, with or without heat pumps, different load sizes and different operational strategies, have been evaluated. The results obtained from different case studies have shown the powerful capabilities of the two simulation programs to provide economic, cost, and sensitivity analyses for a variety of parameters and variables and to optimize parameter values to minimize overall system cost.

Another contribution in the field was made by Lund and Petolla (1992) and Lund (1997) with the development of SOLCHIPS computer simulation tool for optimization of solar heating systems with seasonal storage.

The pre-design tools for CSHPSS MINSUN and SOLCHIPS are fast and easy to use, but they do not provide information for design and optimization of additional system components, e.g., buffer storage tanks when seasonal ground storage is used (Pahud 2000). The TRNSYS program, on the other hand, is a detailed and versatile simulation tool capable of handling many subsystem, user-defined, and case-specific modules. The ability to simulate thermal storage behavior at a more detailed level, e.g., on a system and subsystem level, makes TRNSYS a state-of-the-art tool for detailed design, dimensioning, and optimization of CSHPSS.

Summarizing the findings from computer simulation studies and monitoring campaigns, it is evident that although well developed and also widely used in some countries, the concept of CSHPSS of solar energy requires further research in order to make it economically competitive with conventional energy sources. Research could include studies related to cost reductions for construction of the storage; heat insulation and reduction of storage heat losses; operating temperatures of the storage, solar collectors net, and heat distribution net in regards to efficiently utilizing the low-temperature concept with the use of heat pumps; efficiency of solar collectors; determining of optimal solar collector area and seasonal storage volume; coupling between solar plant and low-temperature heating systems in the buildings; etc.

UTES with heat pumps

UTES and GSHP systems use the underground for exchange of thermal energy for efficient heating and cooling of buildings. The application is based on the natural ground temperature. The GSHP extracts heat from the ground in winter and injects heat in summer. The GSHP technology offers higher energy efficiency for air conditioning compared to conventional air-conditioning systems, because the underground environment provides a lower temperature for cooling, a higher temperature for heating, and experiences less temperature fluctuation than ambient air temperature. These result in a high coefficient of performance (COP) of the heat pump in both heating and cooling modes.

In general, two types of UTES for combined heating and cooling applications can be distinguished: ATES and BTES (Nordell 2000). As discussed in

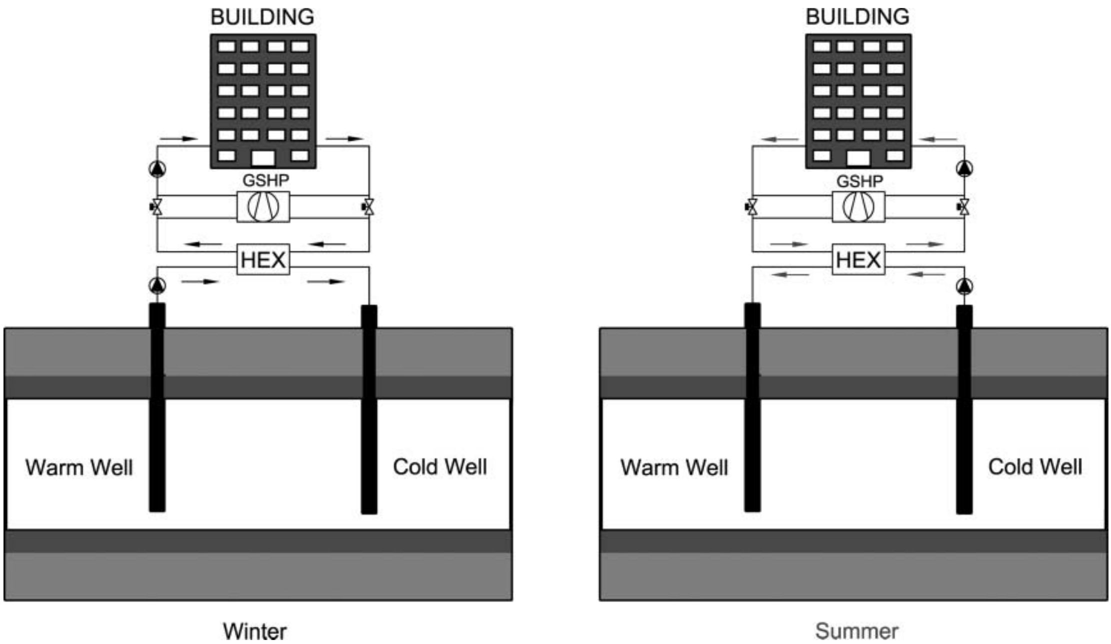

Figure 4. GSHP with aquifer seasonal storage.

the section for seasonal storage of solar energy, for geological or geo-hydrological reasons, it is not possible to construct these systems at any location.

An ATES system is a large open-loop system optimized and operated to realize seasonal TES; the principle is shown in Figure 4. In summer, groundwater is extracted from the cold well and used for cooling purposes. The warmed-up water is injected into the warm well. In winter the process is reversed; water is pumped from the warm well and applied as a heat source, e.g., as a low-temperature heat source for a heat pump. The chilled groundwater is then injected into the cold well again. With ATES, all the water extracted from one well is reinjected in another well. This means that there is no net extraction of groundwater from the soil, which minimizes negative impacts on the environment.

A BTES system consists of a number of closely spaced boreholes; the principle is shown in Figure 5. During the heating season, the borehole heat exchanger is used for extraction of heat from the ground, which serves as a heat source for the heat pump. While the circuit water passes through the heat pump, its temperature cools down. The chilled water is returned in the borehole heat exchanger and the "cold energy" is stored in the ground. During the cooling season, the flow in the BTES system is reversed. The stored cooling energy is extracted and passed through a heat exchanger, providing direct cooling to the building. In periods of peak cooling demand, the (reversible) heat pump can be used. The circuit water will pick up energy from the building and thus be raised in temperature. It will be returned in the borehole heat exchanger where the "warm

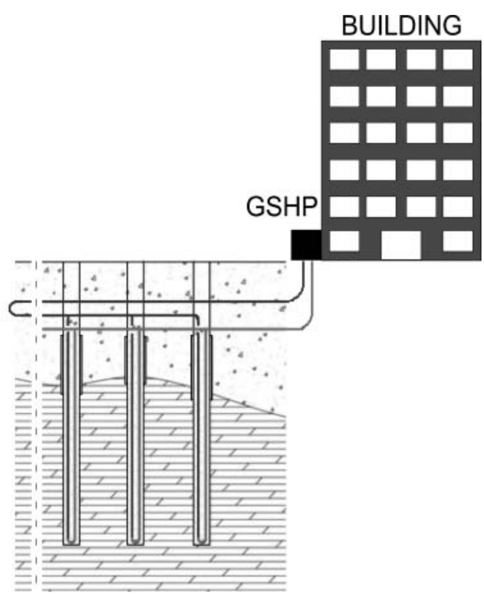

Figure 5. GSHP with borehole seasonal storage.

energy" is stored in the ground for the next heating season.

The development of UTES is strongly supported within the framework of the International Energy Agency (IEA). The IEA Energy Storage Annex 8 is the focal point for all activities related to UTES. Underground heat storage in the temperature range below 40°C (104°F) is usually done to increase the heat-source temperature of heat pumps. High-temperature UTES systems have storage temperatures above 40°C to 50°C (104°F to 122°F). Heat pumps are either used at the end of the storage unloading period, when temperatures drop, or for achieving higher supply temperatures. With increasing temperatures, hydrochemical, biological, and geotechnical problems increase. Annex 12 of the IEA program on Energy Conservation through Energy Storage (IEA ECES) addresses the specific problems of high-temperature UTES.

Cold storage systems with heat pumps have been under investigation by the IEA for many years. Typical modes of operation of such systems are direct cooling in spring and during low-demand periods and cooling by heat pump in summer or during peak-demand periods. These systems substitute chillers, which, compared to thermal storage, have a relatively high energy demand. Seasonal cold storage is now commercialized in some countries. A database made under IEA ECES Annex 7 lists approximately 90 realized projects in the 4 participating countries (Canada, Germany, the Netherlands, and Sweden). Forty of these projects include heat pumps. The size and capacity of cold UTES varies widely. A trend toward very large systems can be seen.

GSHP and UTES systems are applied in various European countries and North America. While, in some countries, these systems are already considered a standard design option for heating and cooling, the technology is quite recent in others. Rybach and Sanner (2000) described the technologies, market situation, future trends, and questions related to GSHP systems development in Europe. Applications and experiences with UTES systems in combination with GSHPs in various European countries were given in Hendriks et al. (2008). A world overview of geothermal heat pump development and utilization was presented by Lund et al. (2004). Status development and applications in the United States and Europe are investigated. Insight into system's efficiency, particularly heat pump COPs in heating and cooling mode, is given.

Comparison of technologies and experiences from pilot projects utilizing the GSHP technology

UTES systems have been used for seasonal storage of large quantities of thermal energy to supply space heating and cooling. UTES systems are most commonly used in combination with GSHPs. Such systems have found broad applications in Europe and North America, with the most common technologies being aquifer storage and borehole storage. Table 4 summarizes some technical data of pilot projects with GSHPs utilizing aquifer or borehole seasonal storage concepts.

ATES

ATES systems require that relatively high well yields can be obtained on site. Because of this, the applicability depends strongly on site-specific hydrogeological conditions. An advantage of such systems is the generally higher heat transfer capacity of a well compared to a borehole. This makes ATES usually the cheapest alternative if the subsurface is hydrogeologically and hydrochemically suited for the system. In recent years, a large number of ATES systems were built in North America and Europe (Bakema and Snijders 1998; Andersson 2007a, 2007b, 2007c; Lee 2010; Hendriks et al. 2008; Sørensen and Qvale 2007; Lund et al. 2004).

The ATES system at the campus of Eindhoven University, Netherlands, is supplying direct cooling in summer as well as low-temperature heating in winter (via heat pumps). It reduces the overall electricity consumption and, consequently, the CO_2 emissions by approximately 20% in comparison with a conventional chiller system (Snijders and Van Aarssen 2003).

The concept and operational experience of the ATES system, which is part of the space-conditioning system for the buildings of the German Parliament in Berlin, was given by Sanner et al. (2005). Simulation studies show heat storage efficiency of 77% and cold storage efficiency of 93% (storage efficiency is ratio of stored to retrieved thermal power). A performed monitoring program shows good agreement between measured and simulated system performance.

In Malmo, Sweden, a residential area uses ATES as part of the district heating and cooling system. The system is delivering free cooling to the district cooling system at a temperature level

Table 4. Technical data of GSHP systems with aquifer seasonal TES.

		System purpose		System capacity, MW (MBtu/h)		Energy delivery, GWh/a (GBtu/a)		Savings		
	Total building area, m^2 (ft^2)	Heating	Cooling	Heating	Cooling	Heating	Cooling	Electricity reduction	CO_2 reduction	References
GSHP with ATES										
Eindhoven (TUe), NL	250,000 (2,690,977)	+	+	20 (68)	20 (68)	25–33 (85–113)	25–30 (85–102)	20%[a]	20%[a]	Snijders et al. (2003)
Berlin (Parliament), DE	—	+	+	—	—	2.05 (7.0)	3.95 (13.5)	—	—	Sanner et al. (2005)
Chr. Hansen A/S, DK	—	—	+	—	3.7 (12.6)	—	6.0 (20.5)	—	468 ton/a	Sørensen et al. (2007), Qvale et al. (1988), Schleisner et al. (1991)
DBI Plast A/S, DK	—	—	+	—	0.175 (0.6)	—	0.875 (2.98)	—	202 ton/a	
Sky-Light A/S, DK	—	—	+	—	0.45 (1.53)	—	3.5 (11.94)	—	686 ton/a	
Billund Lufthavn A/S, DK	—	—	+	—	2.4 (8.2)	—	0.87 (2.97)	—	202 ton/a	
AKV Langholt A/S, DK	—	—	+	—	3.9 (13.3)	—	8.75 (29.8)	—	1290 ton/a	
Malmo, SE	—	—	+	—	1.3 (4.4)	—	3.9 (13.3)	—	—	Andersson et al. (2003) Andersson (2007c)
Stockholm, SE	—	—	+	—	25 (85.3)	—	0.9 (3.1)	—	—	Andersson and Rudling (2000), Andersson (2007b)
Gardermoen Airport, NO	—	—	+	—	8 (27.3)	—	13 (44.4)	—	—	Eggen and Vangsnes (2005)
Louisville, Kentucky, US	161,651 (1,739,997)	+	+	19.6 (66.9)	15.8 (53.9)	—	—	47%[a]	47%[a]	Nordell and Sanner (1998)
PARC, Agassiz, CA	7000 (75,347)	+	+	0.3 (1.0)	0.56 (1.92)	—	—	—	—	Bridger and Allen (2010)
Medicine Hat, CA[b]	12,000 (129,166)	+	+	1.8 (6.1)	1.1 (3.75)	2.7 (9.2)	1.1 (3.75)	—	480 ton/a	Wong et al. (2006)
GSHP with BTES										
Stockholm, SE	—	—	+	—	0.22 (0.75)	—	—	40%[a]	40%[a]	Rybach and Sanner (2000)
Lund, SE	4200 (45,208)	+	+	0.3 (1.0)	0.3 (1.0)	0.395 (1.35)	0.15 (0.51)	—	—	Andersson (2007d)
Falstadsenteret, NO	2850 (30,677)	+	+	0.13 (0.44)	0.13 (0.44)	—	—	—	—	Midttømme et al. (2008)
EANDIS, BE	16,363 (176,129)	+	+	1.9 (6.5)	1.2 (4.1)	0.9 (3.1)	0.824 (2.81)	31%[a]	31%[a]	Desmedt et al. (2008) Desmedt et al. (2010)
UOIT, CA	80,000 (861,112)	+	+	1.4 (4.8)	1.3 (4.4)	—	—	40%h[a]16%c[a]		Dincer and Rosen (2011)
Langen, DE	44,500 (478,994)	+	+	0.33 (1.13)	0.34 (1.16)	0.07 (0.24)	0.06 (0.21)	77%[a]	77%[a]	Sanner et al. (2003)

Note: BE = Belgium, DE = Germany, DK = Denmark, NL = Nederlands, NO = Norway, SE = Sweden, US = United States.
[a]Savings compared to conventional systems supplying the system loads and services.
[b]Pilot project under development.

below +6°C–8°C (42.8°F–46.4°F). A specific variable cost of produced cold of 4 €/MWh (1.54 US $/MBtu) has been evaluated from a monitoring campaign (Andersson 2007c).

ATES is used to serve the district cooling system of a residential area in Stockholm, Sweden. The system has been designed for 25 MW (85 MBtu/h) free cooling power at a storage temperature of +4°C to +14°C (+39.2°F to +57.2°F). During the first year of operation (1999), a low storage efficiency of 60% was monitored. In following years, the efficiency has gradually increased due to a better operational strategy (Andersson 2007b; Andersson and Rudling 2000).

The ATES system at Oslo's Gardermoen International Airport in Norway covers the total cooling needs of the airport, of which 25% (2.8 GWh/a [8536 MBtu/a]) is free cooling via direct heat exchange with cold groundwater and 75% (8.5 GWh/a [29,002 MBtu/a]) is active cooling via the use of heat pumps. The estimated payback time, compared to traditional heating and cooling systems, is less than four years (Eggen and Vangsnes 2005).

One of the largest ATES installations in the United States is in Louisville, Kentucky (Nordell and Sanner 1998). The GSHP system is providing 15.8 MW (53.95 MBtu/h) of cooling and 19.6 MW (66.92 MBtu/h) of heating capacity. The energy consumed is approximately 53% of an adjacent similar non-GSHP building, saving $25,000 per month.

The Pacific Agricultural Research Centre (PARC) in Agassiz, Canada, employs ATES to supply heating and cooling to a 7000 m^2 (75,350 ft^2) facility. The system provides free cooling and heating via heat pump. Estimated peak cooling and heating capacities are 563 kW and 293 kW (1.92 MBtu/h and 1 MBtu/h), respectively. There is no sufficient operational data from system monitoring campaigns (Bridge and Allen 2010).

A pilot project for an ATES system combined with GSHP is currently under development for a commercial building of 12,000 m^2 (120,000 ft^2) in Medicine Hat, Canada. The system is designed to provide 90% of the annual cooling demand by direct cooling and 57% of the annual heating demand via the GSHP. The system should provide a net greenhouse gas (GHG) emissions reduction of 480 tonnes per year compared to a conventional energy system (Wong et al. 2006).

BTES

Closed-loop BTES systems depend less on site-specific hydrogeologic conditions than ATES systems and are better suited for areas where relatively high well yields are not obtainable. In addition, since the systems are operated in a closed loop (i.e., there is no contact between natural ground water and the heat exchange fluid), they have the potential to find much wider applications compared to ATES. A disadvantage of this concept is the relatively high construction cost, mainly due to drilling.

The largest BTES system in Sweden so far is located in Stockholm, offering 220 kW (751,174 Btu/h) of cooling from 30 borehole heat exchangers (BHEs) (Rybach and Sanner 2000). During a ten-year period, a saving of 40% of costs compared to conventional alternatives is expected.

Monitoring data of a small BTES for heating and cooling of the astronomy house in Lund, Sweden, comprised of 20 boreholes, were given by Andersson (2007d). Data from 2002 shows that during summer, the system delivered free cooling of 150 MWh (512 MBtu) at a COP of approximately 50. During winter, the COP of the total system (ground store and heat pump) has been 4.8, approximately 300 MWh (1024 MBtu) of heat and 95 MWh (324 MBtu) of electricity. The estimated payback period for the system has been ten years.

Midttømme et al. (2008) provided information on GSHPs with BTES in Norway. A new BTES system has recently been completed for a museum in Levanger. The heating and cooling scheme comprises a 130-kW (0.444-MBtu/h) heat pump and nine 180 m (590.6 ft) deep boreholes. The payback time for the extra capital costs of the ground-source system, compared to a conventional heating and cooling system, is estimated to be 12 years.

Desmedt et al. (2008) and Desmedt and Van Bael (2010) presented the results from a feasibility study to the implementation phase of vertical grand heat exchangers (GHEs) in combination with a GSHP for a Belgian office building. The energy savings, optimal configuration, and environmental benefits offered by using this system were calculated. Simulation results show that primary energy savings and CO_2 emission reduction of 31% can be obtained compared to classic primary energy consuming technologies. The ground storage system supplementary investment is paid back in eight years.

A large scale BTES system of Ontario Institute of Technology (UOIT), Canada, was presented by

Dincer and Rosen (2011). The system has 380 boreholes, each 213 m (700 ft) deep, and is a critical component of the university's heating and cooling system. Monitoring results show annual energy savings for heating and cooling of 40% and 16% respectively. A payback period of 7.5 years is expected.

The German Air Traffic Control headquarters in Langen has been conceived as a low-energy office (Sanner et al. 2003). The BTES field comprising 154 BHEs is integrated into the heating and cooling system of the building. The BTES supplies a total cooling capacity of 340 kW (1.16 MBtu/h) and heating capacity of 330 kW (1.13 MBtu/h), representing 80% of the annual cooling and 70% of the annual heating requirements.

Operational experiences and design considerations for GSHP with seasonal storage

The use of ground-coupled systems in buildings offers economic as well as environmental advantages. When both heating and cooling is required, a ground-coupled system can function both as a heat source and a heat sink. These double-effect storage projects are more likely to be economical.

Experiences from ATES pilot projects and demonstration plants show storage efficiencies of 60% to 90% (Sanner et al. 2005; Andersson 2007b, 2007c). Primary energy savings and CO_2 emission reductions vary from 20% to 50% in the different projects (Snijders and Van Aarssen 2003; Nordell and Sanner 1998). These systems show high potential for free cooling operation, the concept of which has been widely utilized in the projects discussed in this article. For heating purposes, temperature upgrade by heat pumps is needed.

Experiences from BTES pilot projects and demonstration plants have shown primary energy savings and CO_2 emission reductions from 16% to 40% in the different projects (Fellin and Sommer 2003; Rybach and Sanner 2000; Desmedt et al. 2008; Desmeth and Van Bael 2010; Dincer and Rosen 2011). Estimated payback periods for the different projects have resulted in 8 to 12 years. Compared to systems with ATES, BTES systems show less potential for free cooling operation, mainly for a period at the beginning of the cooling season. Due to the low heat transfer rates between borehole heat carrier fluid and the surrounding ground, and heat up of the storage, reverse heat pump operation mode is used to supplement cooling operation. For heating purposes, the ground storage supplies low-temperature heat to heat pump evaporators.

GSHP projects with ATES and BTES have high investment costs. Therefore, detailed system simulation models are needed for design and dimensioning. Comprehensive thermodynamic analyses, evaluating thermal storage in aquifers for space heating and cooling, were performed by Carotenuto et al. (1990). A procedure for a numerical evaluation of the system performance and optimization is presented in a convenient form for system development and application.

Kangas and Lund (1994) developed a computer model AQSYST for simulating energy systems employing ATES. The model has been used to study the application of different types of aquifers for seasonal storage of thermal energy. Simulation results suggest that high-temperature storage (60°C–90°C [140°F–194°F]) is feasible only in stagnant aquifers, whereas for low-grade heat (15°C–20°C [59–68°F]), aquifers with high natural flows can be used (500–600 m/y [1500–1800 ft/y]).

Various analytical and numerical solutions have been developed and used as design/research tools to predict the short- and long-term response of BTES systems. Table 5 summarizes some of the most significant contributions to modeling the short- and long-term response of borehole ground heat exchanger systems.

Single borehole systems can be designed by considering only the long-term thermal response of the borehole. For multiple borehole systems, used for energy storage, the short-term response of the borehole has significant impact on the efficiency of the whole GSHP system. When determining the short-term response, the borehole thermal capacitance and both the filling material of the borehole and the heat carrier fluid inside the ground heat exchanger should be considered. Short-term response of the ground is critical during heat flux build-up stages and for cases with both heating and cooling demands. Determining the hourly thermal energy use and the electrical demands of GSHP systems also requires the short-term response of the ground to be considered.

The approach of Eskilson (1987) for numerical modelling of the thermal response of borehole systems using non-dimensional thermal response functions (*g*-functions) is considered state-of-the-art and has been implemented in software like EED (Blomberg et al. 2008), TRNSYS (Claesson et al. 1981; Hellström 1989; Mazzarella 1989; Pahud 1996; Klein 2004), HVACSIM+ (Clark 1985), and GLHEPRO (Spitler 2000).

Table 5. Mathematical models for design and dimensioning of borehole heat exchangers.

Model types	Reference
Long-term response of BTES systems	
- Line source theory	Ingersoll et al. (1954)
- Cylindrical source theory	Ingersoll et al. (1954), Kavanaugh (1985), Bernier (2001), Bernier et al. (2004), Nagano et al. (2006)
- Numerical non-dimensional *g*-functions	Eskilson (1987)
- Analytical *g*-functions	Eskilson (1987), Zeng et al. (2002), Lamarche and Beauchamp (2007a), Bandos et al. (2009)
- Capacity-resistance model (CaRM)	Zarella et al. (2010)
Short-term response of BTES systems	
- Short time-step *g*-functions	Yavuzturk 1999; Yavuzturk and Spitler 1999, 2001; Xu and Spitler 2006
- Analytical solutions for short-term response of borehole heat exchangers	Young (2001), Lamarche and Beauchamp (2007b), Bandyopadhyay et al. (2008), Javed 2010
- Capacity reistance model with short-term response modelling (CaRM)	Zarella et al. (2011)

In order to design efficient ground-coupled systems for the heating and cooling of buildings, temperature levels, surface areas of room heaters/coolers, performance characteristics of heat pumps, heat exchangers, circulation pumps, borehole geometry (aquifer characteristics), and cooling/heating demand of the buildings must be taken into account to achieve an optimal system that works efficiently in economical and technical terms.

For UTES systems, one of the most important external factors is the required temperature level for the heating/cooling case involved. TES systems become more efficient if the temperature requirement for space heating is low, about 35°C (95°F), and if the temperature for cooling is high, about 15°C (59°F). In that case, low temperature difference between the store and demand side will be present and also the heat pump would operate at lower temperature difference. Proper design will result in high COP for the whole system. However, this would require the use of low-temperature heating and high-temperature cooling radiant system in the building. Thermo-active building systems (TABS) for office and commercial buildings, and floor heating/cooling systems for single- and double-family residential houses, have proven successful in practice.

In Fellin and Sommer (2003) simulation analysis of an office building equipped with a thermal slabs system was presented. Two different climatic zones, two different strategies of ventilation, and two possibilities of plant—a traditional plant (low-temperature gas boiler and air-condensed chiller) and an innovative plant based on a GSHP—were studied. The results show that, by using a ground-coupled heat pump, more than 40% of energy can be saved compared to the use of a conventional system. The utilized advantages here are that the heat pump is coupled with a low-temperature heating and high-temperature cooling system (TABS), and in this particular building simulation, the temperature required for slab heating in winter is only 35°C (95°F) and for slab cooling in summer is 16°C (61°F).

For sizing GHEs, such properties as undisturbed ground temperature, ground thermal conductivity, borehole thermal resistance, and specific heat capacity are needed to deliver thermal energy at a proper temperature (Signorelli et al. 2004). The thermal efficiency of the BTES depends on the soil properties, ground water movement, temperature, and characteristics of the thermal store itself (geometry, borehole spacing, grouting material, pipe thermal conductivity) (Gehlin and Nordell 1997; Pahud and Matthey 2001; Zeng et al. 2003; Hellström 1991; Kjellsson and Hellström 1997; Hellström et al. 1988; Lund 1985; Reuss et al. 1997).

The design of GSHP with GHEs is influenced by the heating and cooling load characteristics of the building (load pattern), the size of the ground system (depth and number of boreholes), and the geometry of the ground system (configuration, i.e., positioning of the boreholes). The maximum and minimum design water temperature from the ground loop and the annual heat rejection to and extraction from the ground loop are important parameters.

Naumov (2005) studied, through computer simulations with EED software, the influence of the heating and cooling load characteristics of the building (load pattern), the size of the ground system (depth and number of the boreholes), and the geometry of the ground system (configuration, i.e., positioning of the boreholes) on the overall efficiency of a GSHP system. Simulation results have shown that the brine temperature (mean brine temperature in the boreholes) differences for different borehole configurations using the same specific borehole load (ratio between building heating and cooling needs and total borehole length) are not very large, being within 1–2K. On the other hand, changes in the specific borehole load have a large influence on ground system performance, and a mean brine temperature difference of 4–8K is needed for a specific borehole load increased with 200%–400%. Obviously, the larger the energy need of the building, the larger demand there is for the ground system and vice versa. For example, larger demand means that the total borehole length should be larger in order to keep the mean brine temperature within required limits for heat rejection/extraction.

Furthermore, simulations have shown that a system with balanced heating and cooling and storage (rectangular borehole layout) is more sensitive to the accuracy of the assumed load pattern than is a system for heating or cooling only (linear borehole layout). That is explainable by the fact that the requirements for the configuration of the boreholes are set by the share of the heating and cooling of the total energy need of the building. For example, if there is a heating- or cooling-dominated situation, then the heat exchange area of the ground system should be maximized to enhance the rejection of thermal energy in the ground and avoid heat accumulation or depression during long-term operation. In that case, linear borehole geometry is preferable. With a balanced heating and cooling situation, however, a rectangular layout with storage capability is advantageous in terms of seasonal energy performance. However, any significant deviation from that balance (assumed load pattern) will have significant influence on the long-term performance of the system (time span of ten years considered), which has been confirmed by the simulation results. The models developed in the work of Naumov (2005) together with the design software were applied in a case study (Astronomihuset, Lund). Simulated and measured data agreed reasonably well. Detailed results of the simulation and monitoring study are presented in the given references.

Regardless of the high energy-saving potential and the intensive technological development in recent years, GSHP systems with BTES wide application has been obstructed by the high investment costs associated with installing a ground loop to meet peak cooling or heating load. From another side, GSHP systems with ATES have considerably lower investment costs, but these systems are dependent on the availability of suitable natural aquifers at the site. An alternative design for ground-source systems is the hybrid system. This approach, widely considered a variation of the ground-coupled to GHEs design, utilizes the use of a cooling towers (in cooling-dominated commercial buildings) or boilers (in heating-dominated residential buildings) in parallel with the GSHP system. The use of a cooling tower or a boiler allows the designer to size the ground loop for the smaller of the heating or the cooling loads and use the GSHP in combination with the cooling tower to meet the peak cooling demand or with the boiler to meet the peak heating demand. The hybrid equipment preserves some of the energy efficiency of the system but reduces the capital cost associated with the ground loop installation. In addition, such a hybrid system would allow balancing the seasonal heating and cooling loads for the ground loop. The excess of building heating or cooling loads in a heating- or cooling-dominated building will be handled by the hybrid part of the system, and heat accumulation or depression in the ground system will be avoided, thus allowing design of the borehole layout in a way to benefit from seasonal storage of thermal energy.

Rafferty (1995) evaluated through numerical calculations the capital costs associated with ATES, BTES, and hybrid-BTES ground-source designs for cooling-dominated commercial buildings. Specifically, the costs considered are those associated with the heat source/sink or the ground portion of the system. The heat rejection over the three designs has been standardized, assuming constant heat pump loop temperature conditions, permitting in that way a direct comparison of the three systems. Considering the same building load for the three system types, cost calculations were made for a wide variety of soil (or groundwater) temperatures, well depths (groundwater), loop lengths (ground coupled), and tower-loop ratios (hybrid system). Results show that at system capacities of 100–175 tons (351.7–615 kW) and above, the ATES system has a capital cost advantage over hybrid BTES and BTES systems. Below this range, the hybrid system is the most attractive. Only for systems with very low capacities (less than 100 tons [351.7 kW]) and very deep aquifer depths (more than 800 ft [244 m]) will the ATES system capital cost exceed that of the BTES. Detailed results are given in Rafferty (1995).

In a recent study, Hackel and Petzborn (2011) analyzed, through computer simulations with TRNSYS, the energetic and economic performance of three hybrid-BTES GSHP installations in the United States compared to a BTES and a conventional HVAC. Two of the installations were for a cooling-dominated commercial buildings located in Las Vegas (NV), and one was for a heating-dominated residential building in Madison (WI). The results show that all three hybrid installations were economically cost effective. The average rate of return for investing in hybrids in these three cases has been 10% compared to a conventional HVAC system. The additional investment for a full BTES ground-source system would result in an average rate of return of just 3%.

The study of Hackel and Petzborn (2011) has shown the importance of component sizing in a hybrid system. Care should be taken not oversize the load that drives the GHE size. In addition, optimizing algorithms for proper sizing and operational modes of hybrid equipment (cooling towers and boilers) should be used. Circulation pumps use a lot of energy in a hybrid system, and due to that fact, pump sizes should be minimized and the focus should be on part-load operation. Variable-speed pumps should be used whenever possible. For the heat pump operation, large peaks should be avoided.

Basic design information for hybrid GSHP systems was given in Kavanaugh (1998), while in Xu (2007), optimal control strategies for these systems were developed.

As some authors suggest, the development of a unified simulation model for the combination of ground system, heat pump, heat exchanger, and building installations would be a useful task for future research. Future research should also include more-detailed GSHP system designs, including storage pattern and geometry and coupling to low-temperature heating and high-temperature cooling building systems. Additionally, new designs validation through measurements in different types of buildings would boost technological development of the concept.

Future prospects—TES in sustainable buildings

Seasonal TES is a mature technology that has been applied successfully throughout the world in residential, commercial, and institutional building applications. Energy sources include electric heat pumps, solar energy, winter ambient air, and waste thermal energy like industrial process heat. The concept has often been applied in standard buildings with the objective to demonstrate that the energy storage techniques could be successfully applied rather than to optimize the building performance. Indeed the design of the building and the design of the energy storage were often not coordinated, and energy storage simply supplied the building demand, whatever it might be.

Sustainable buildings need to take advantage of renewable and waste energy to approach ultra-low energy and zero-emission buildings. Such buildings will need to apply TES techniques customized for smaller loads and community-based thermal sources. Lower exergy heating and cooling sources will be more common. Utilization of low-exergy heating and cooling sources requires that energy storage is intimately integrated into sustainable building design.

A coordinated set of actions for improved seasonal UTES design and sizing is needed if the potential benefits are to be fully realized. Well-designed UTES systems can reduce initial and maintenance costs and can significantly reduce energy use and demand. Increased flexibility of operation, improved indoor environmental quality, conservation of fossil fuels, and reduced pollutant emissions are other benefits.

At present, IEA ECES Annex 23 "Applying Energy Storage in Buildings of the Future" is dealing with integration of energy storage in ultra-low-energy buildings.

Conclusions

Seasonal UTES is advanced energy technology, and there has been increasing interest in using it for thermal applications, such as DHW and space heating and cooling. Within the contents of this literature review article, the current status in the development and implementation of UTES has been investigated. The different energy storage concepts have very different characteristics, possible applications, strengths, and weaknesses. This study aims to motivate and provide the basis for the development of new intelligent TES possibilities in buildings.

The selection of an UTES system mainly depends on the energy source, local geo-hydrological site conditions, economic viability, and operating conditions. Specific parameters that influence the viability of a UTES system include facility thermal loads, thermal load profiles, availability of waste or excess thermal energy, availability of natural and renewable energy sources, type of thermal generating equipment, and building type and occupancy. The economic justification for a UTES system usually requires that annual capital and operating costs are less than the cost for conventional systems and equipment supplying the same service loads and periods. Well-designed systems can reduce initial and maintenance costs and energy use and demand. Although the different seasonal UTES solutions have found many applications in practice, it is still not clear how these can best be integrated into ultra-low-energy and zero-emission buildings that are capable of being replicated in a variety of climates and technical capabilities. Detailed studies on the dynamic performance and control strategies of the energy storage systems for different building types, weather conditions, and user behavior should be performed. Advanced design strategies for UTES solutions should be developed.

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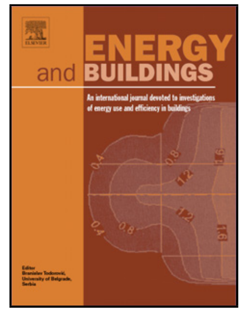

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Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels

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Highlights

- An HVAC system for a single family house is designed and simulated
- HVAC system consists of various energy efficient components
- A custom-made PV/T panel is designed and integrated into the HVAC system of the house

- The house has its own electricity and heat production via PhotoVoltaic/Thermal panels (PV/T)

Due to the energy efficient HVAC system and its own energy production, the house produces more electricity than it consumes, annually

Abstract

Present work addresses the HVAC and energy concerns of the Technical University of Denmark's house, Fold, for the competition Solar Decathlon Europe 2012. Various innovative solutions are investigated; photovoltaic/thermal (PV/T) panels, utilization of ground as a heat source/sink and phase change materials (PCM).

The development of a building integrated photovoltaic/thermal (BIPV/T) system and its performance evaluation compared to a PV installation built of the same photovoltaic cells are also presented. Annual results show that having the combined PV/T system is more beneficial compared to having two separate systems.

PV/T panels enable the house to perform as a plus-energy house. PV/T also yields to a solar fraction of 63% and 31% for Madrid and Copenhagen, respectively.

The ground heat exchanger acts as the heat sink/source of the house. Free cooling enables the same cooling effect to be delivered with 8% of the energy consumption of a representative chiller.

The major part of sensible heating and cooling is done via embedded pipes in the floor and ceiling. Ventilation is used to control the humidity and to remove sensory and chemical pollution.

A combination of embedded pipes and PCM was simulated. Results show energy savings up to 30%, for cooling season in Madrid.

Keywords - Solar Decathlon Europe; Fold; phase change materials; ground heat exchanger; radiant heating and cooling; photovoltaic/thermal; domestic hot water tank; Tichelmann; drain-back system

1. Introduction

Buildings play a key role within the 20-20-20 goals of the European Union due to the fact that they are responsible for 40% of the energy consumption within the member states [1]. Therefore an urgent and effective transition is necessary in order to reach to the almost passive house levels dictated by various standards.

These goals are in parallel directions with the main goals of the competition, Solar Decathlon, where the main goal is to design, build and operate an energetically self-sufficient house that uses solar energy as the only energy source [2].

Technical University of Denmark, herein DTU, joined the competition, Solar Decathlon Europe 2012 with the house "Fold". During the course of this study, an entire HVAC system for a single family house has been designed, simulated and tested.

A house, other than just providing shelter, should also be able to provide necessary and optimal thermal comfort (including indoor air quality) for the occupants however this goal should be achieved with the lowest possible energy consumption. The design of the HVAC system intended to satisfy both of these needs. Innovation was a driving force and this was achieved via taking advantage of well-known and proven systems and integrating them into the HVAC system and coupling them with relatively less mature technologies.

The HVAC system of the house consisted of: ground heat exchanger (GHE), embedded pipes in the floor and in the ceiling, ventilation system (mechanical and natural), domestic hot water (DHW) tank and photovoltaic/thermal (PV/T) panels placed on the roof. The design methodology, further information about the components and main results are presented in the following chapters.

2. Design of the house

The project being multi-disciplinary by its nature, some of the design values and parameters were fixed without the possibility of alteration. Also some of the design values were fixed due to the commercially available products and their capacities.

The house is a detached, one-storey, single family house with an indoor floor area of 66.2 m2 and with a conditioned volume of 213 m3. The design of the house intends to minimize heat gain to the house from the ambient. The house's largest glazing façade is oriented to the North side, with a 19˚ turn towards West.

The house is constructed from wooden elements. Walls, roof and floor structures are formed by placing prefabricated elements in a sequential order and sealing the joints. North and South glazed façades are inserted later and the joints between glazing frame and house structure are sealed.

Prefabricated house elements are made from layers of wooden boards, which in combination with I beams in between forms structural part and mineral wool insulation. The house is insulated with two types of insulation; 20 cm of conventional mineral wool and 8 cm of compressed mineral wool.

The glazing surfaces in North and South sides of the house are covered by the overhangs which eliminate direct solar radiation to the house during the summer season. For the winter season direct solar radiation enters the house, creating a favorable effect. No active shading systems were installed in the house except for the skylight window.

Inside the house, there is a single space combining kitchen, living room and bedroom areas. Shower and toilet areas are partly separated by partitions. Technical room is completely isolated from the main indoor space, having a separate entrance. Wall between technical room and indoor space is insulated with the same level of insulation as the outside walls. The house, structural element and respective areas can be seen in Figure 1 and Table 1:

Insert Figure 1 here

Insert Table 1 here

The house is a fully functioning house therefore it is equipped with different appliances such as: PC, refrigerator/freezer, clothes washer, clothes dryer, dish washer, oven, TV and DVD player. Electrical power of the installed equipment is 1.5 kW.

3. Design methodology of the HVAC system

With the given constraints on the system, an entire HVAC system for the house had to be designed following the ambitions given in the introduction.

To design a heating/cooling and ventilation system, load calculations were performed. Construction of the house is defined by the architectural design team. This design was taken as the basis for load calculations. Even though the idea behind the architectural design of the house was to adjust certain parameters such as, orientation, tilt of the roof and walls, glazing areas etc. this option was not realized in the simulations and in the calculations.

The initial design conditions required for the house to be fully functioning in two different climates: Denmark (Copenhagen) and Spain (Madrid). The resulting heating and cooling needs are as follows: maximum cooling load is 52.0 W/m2, average cooling load is 35.2 W/m2, maximum heating load is 45.6 W/m2 and average heating load is 26.6 W/m2, given the indoor floor area of 66.2 m2

Even though the design was mainly aimed at keeping the conditions during the competition period, it had to be assured that the house performs as intended all year round. This was implemented with different set-points in the simulations as explained in the respective chapter.

The only electrical energy source to the house is solar energy, utilized via photovoltaic panels placed on the entire roof area. The electrical system is designed to be grid-connected with no batteries. Coupled with the photovoltaic panels is the thermal system, which absorbs the heat produced by photovoltaic panels and utilizes it in the DHW tank, making combined photovoltaic/thermal system (PV/T).

Cooling and heating system of the house is water based, with low temperature heating and high temperature cooling principle. Heat source/sink is the ground, utilized via a borehole heat exchanger. Free cooling is obtained during the cooling season without any extra energy consumption other than the circulation pump and ground coupled heat pump is used to achieve the necessary supply temperature to the embedded pipes during the heating season.

As an addition to the space heating and cooling, ground heat exchanger could also be utilized for the PV/T cooling. Yet, initial evaluations showed that this concept was too expensive to be realized, since it requires extra capacity of the ground heat exchanger.

In order to regulate the air quality in the house, mechanical and natural ventilation systems are installed. The mechanical ventilation consists of 2 supply diffusers to the space and 4 exhausts (kitchen hood, bathroom, toilet and the clothes dryer).

To increase the building's thermal mass, an option of installing Phase Change Material, herein PCM, into the structure of the building was considered. The model of active cooling using PCM was chosen. Pure PCM material is stored in a metal container. The container is equipped with a piping system, to discharge the heat stored in the material.

The house being high-tech, it stores great amount of machinery and electronic equipment which operate the house. All of these components release heat to the environment. As it is a need to limit heat production in the house, a solution is to isolate all equipment which is not used by the occupants on a day to day basis. The equipment is placed in the technical room, which has no direct thermal connection to the inside area.

4. Design methodology of the PV/T system

In order to justify the advantages of combining electrical and thermal part in one element, various investigations were carried out. The main goal was to keep the cell temperature under control and keep the electrical efficiency close to the nominal value and also to utilize the heat that is gained from cooling the cells for the various heating needs of the house (domestic hot water, hot water consuming appliances, but not space heating). Special attention was given to the hydraulic division of PV/T panel, to the practical solution for dismountable joints between panels and to the common design of thermal and electrical parts.

4.1 Test of the thermal part

Parametric analyses were made in order to find out the panel's effectiveness in relation to different configurations of lateral pipes, 6 and 10 per meter, Figure 2. It can be observed from Figure 2 that spacing of 100 mm can utilize more solar energy than spacing 166 mm. The most significant difference appears when the temperature difference between surrounding and PV/T surface is negligible.

Insert Figure 2 here

Temperature fluctuation across the absorber plate for two different spacing of lateral piping in PV/T panel can also be seen in Figure 2. The calculation was carried out for solar irradiation of 1000 W/m2, 25°C and no wind. The peaks indicate intermediate space between two pipes where the temperature raises the most. It was desired to have as even temperature over the absorber as possible, thus spacing of 100 mm was chosen.

The PV/T panel was tested at an outside testing facility, with a tilt of 67.5° from the horizontal and oriented to the true South, the test setup can be seen in Figure 3.

Insert Figure 3 here

The expressions used to calculate the efficiencies are as following:

$$\eta_{Thermal\ with\ active\ cells} = 0.422 - 5.628 \cdot \Delta T/G \qquad (1)$$

$$\eta_{Thermal\ with\ passive\ cells} = 0.483 - 5.485 \cdot \Delta T/G \qquad (2)$$

Insert Figure 4 here

Thermal efficiency was measured under two circumstances: with active and passive PV cells. In the case with active cells (1), 42.2% of solar irradiation was transformed to heat. During the measurement with passive cells (2), efficiency of 48.3% was reached. The difference is due to the conversion of irradiation into electricity.

4.2 Test of the electrical part

Electricity was generated by mono-crystalline silicone cells. Squared cells were divided into 3 rectangular pieces with dimensions of 41x125 mm to decrease the risk of failure due to panel bending. It is also possible to cover a larger area with smaller cells. The by-pass diodes were integrated inside the lamination (8 and 14 cells per diode). Thus, in case of failure, only a certain number of cells are out of order and the panel still produces power. No junction boxes were used for the PV/T modules; only fixture for cable outlets.

The electrical testing was performed on the same test setup as the thermal test. Voltage and current were measured using the “Uganda” method, as seen on Figure 5.

Insert Figure 5 here

Insert Figure 6 here

The expression used to calculate the efficiency is as following:

$$\eta_{PV\ cells} = 0.159 - 0.583 \cdot \Delta T / G \qquad (3)$$

Insert Table 2 here

The results of the electrical tests, Figure 6, showed that the efficiency curve depends on solar irradiation and temperature difference between panel and the ambient. The electrical test of the panel was done under moderate Danish summer weather conditions, temperature and irradiation values can be seen in Table 2. The efficiency curve was idealized and divided into two zones representing electrical efficiency when the cells are actively cooled by fluid circulation and to when the panel is cooled only naturally. The three marked efficiency levels correspond to Standard Test Conditions but with varying panel temperature. The three different efficiency levels illustrate these scenarios; 32°C for PV/T cooling via ground; 35°C for PV/T charging the DHW tank and 66°C for normal PV panel operation.

The electrical characteristics of the PV cells stayed unchanged regardless of the cooling mode, but the active cooling provided higher electrical efficiency, in comparison to PV with the same boundary condition.

A new type of efficiency, hybrid efficiency, was introduced. Up to 58% of the solar energy, that is incident on the surface of the PV/T panel, is utilized, seen on (4). The hybrid efficiency, Figure 7, represents sum of electrical efficiency and the thermal efficiency if both systems work simultaneously.

$$\eta_{PVT\ hybrid} = 0.583 - 6.281 \cdot \Delta T/G \qquad (4)$$

Insert Figure 7 here

5. HVAC system and control concept

The individual operation of the components of the HVAC system and operation of the system as a whole had to be controlled in order to assure optimal performance. This was mainly done on a seasonal basis (heating/cooling) and with more detailed conditions within each season.

The most significant parameters of the HVAC system and how they interact with the rest of the components are presented below:

The ground heat exchanger was designed to be a borehole with a depth of 120 meters, single U-tube configuration and with a diameter of 0.12 m. The inner and outer radii of the heat exchanger pipes were 0.013 m and 0.016 m, respectively. Obtained borehole resistance was 0.1 m-K/W and total resistance to the undisturbed ground (8.3°C and 14.3°C for Copenhagen and Madrid, respectively) was 0.37 m-K/W.

The space heating and space cooling in the house is provided by the pipes that are embedded in the floor and the ceiling. It is a dry radiant system, having piping grid installed under the wooden layer, with an aluminum layer for better thermal conductance. Space heating is only obtained by the embedded pipes in the floor and space cooling is obtained by embedded pipes in the ceiling and, if necessary, in the floor. The supply and return flows will be coming from/going into the installed ground heat exchanger. In order to control the water flow and the supply temperature, a mixing station is installed.

The details of the embedded pipe system are as following:

- Ceiling; foam board system, with aluminum heat conducting device, PEX pipe 12x1.7 mm. In total 6 circuits are designed for the ceiling system, with maximum flow rate in one circuit of 0.07 m3/h.
- Floor; chipboard system, with aluminum heat conducting device, PEX pipe 17x2.0 mm. In total 4 circuits are designed for the floor system, with maximum flow rate in one circuit of 0.07 m3/h for the cooling case, and 0.15 m3/h for heating case.

The installed air handling unit, herein AHU, can provide an air flow rate up to 320 m3/h, which is 1.5 ach at 100 Pa. This flow rate fully covers the need for the design flow rate.

AHU has two heat recovery systems: passive (cross flow heat exchanger) and active (reversible heat pump coupled with the DHW tank). Active heat recovery is obtained via a heat pump cycle that changes the evaporator/condenser in the supply air duct to the interior. This is achieved via a 4-way valve in the heat pump cycle. Passive heat recovery system has an efficiency of 88% (sensible heat). Thermal energy of the exhaust air is transported to the supply air. By pass mode is possible.

Mechanical ventilation gives more control over the parameters like temperature, relative humidity and CO2 levels however due to the use of mechanical fans it consumes a certain amount of energy (40 Wh/m3). This amount of energy can be eliminated when the outside conditions are feasible for natural ventilation. Natural ventilation option is possible via two windows in South and North façades and the operable skylight window.

PV/T part could also directly interact with the ground. PV/T part is intended to produce electricity and produce heat for domestic hot water and domestic appliances (dishwasher, clothes washer and clothes dryer).

PV/T area (67.8 m2) is hydraulically divided into Part A (45.4 m2, 3x3 m PV/T panels) and Part B (22.4 m2, 2x2 m PV/T panels), for different control purposes and also for lowering the pressure drop on supply/return piping. Part A is solely intended to charge DHW tank. If there is any flow in Part A this is when there is a DHW need and the flow can only be directed to the DHW tank.

On the other hand, Part B serves for two purposes; charging the DHW tank and PV/T cooling. When there is a DHW need, Part B also contributes to the charging of the DHW tank. Initial simulations and calculations showed that the ground (one borehole) is not capable of providing necessary supply temperature to the embedded pipes when house cooling and PV/T cooling are active simultaneously. Therefore PV/T cooling option is only applicable when house doesn't need cooling.

The PV/T panels were interconnected in 6 separate electrical strings. The most of the strings were made of 448 full cells (3 cut cells) with nominal voltage of 298 V (0.66 V per cell) and short circuit current of 8 A. Total installed nominal power was 10.8 kWp that was electronically cut down to 9.2 kWp by two inverters. In total, 9914 cells were used with a cell area of 50.8 m2.

A drain-back tank was included in the thermal circuit, between the PV/T loops and the DHW tank. All piping in the level above the drain back tank was constructed with a minimal slope of 2% to the reservoir. In idle pump mode, the heat transfer medium is drained from the collectors into the 100 l reservoir tank, from where the liquid fills the collectors when the pump starts.

Low-pressure drop of the solar thermal part with Tichelmann connection is using the drain-back tank system. This combination allows the operation of the system without any additional anti-freeze liquid, free of thermo-syphoning effect and without boiling or freezing risk in any climate around the world.

To keep as much equal flow rate per square meter across the array as possible the flow was optimized by various diameters of piping and by balancing valves. The balancing was done in situ when the Fold was assembled in Madrid.

The DHW tank of 180 liters is equipped with two spiral heat exchangers and an electric heater. One of the spiral heat exchangers is connected to the PV/T loops via the drain-back tank and the other one to the active heat recovery system of the ventilation. The top part of the tank (54 liters) is heated by the electric heater (1.5 kW).

6. Dynamic simulations of the house

In order to evaluate all year round performance of the house, commercially available dynamic building simulation software, TRNSYS [7] was utilized.

Simulations were carried out for Copenhagen and Madrid. Weather files used were; International Weather for Energy Calculations (IWEC) and Spanish Weather for Energy Calculations (SWEC), respectively.

May to September months (both included) were considered as cooling season and rest of the months were considered as heating season. Relative simulation parameters were adjusted accordingly.

Same load profiles for occupants, lighting and equipment were implemented for Copenhagen and Madrid. . There are 2 occupants in the house with 1,2 met. Occupants are assumed to be away from 8:00 to 16:00 during the weekdays and from 12:00 to 17:00 during the weekends.

The lighting load is 222 W (3,4 W/m2). Lights are assumed to be ON from 05:00 to 08:00 and from 16:00 to 22:00 every day. Different equipment is ON and OFF during the day. Following values are expressed with respect to the maximum value; for the weekdays, load is 5% all the time except from 02:00 to 03:00 where load is 20% and except from 19:00 to 20:00 where load is

62%. For Saturday, from 7:00 to 8:00 the load is 15%, from 8:00 to 9:00 the load is 34% and for Sunday from 2:00 to 3:00 the load is 20%.

Set-points for the temperature has been defined as 21°C±1 K for heating and 25°C±1K for cooling season, following [8]. These values refer to the Category 2 of comfort conditions for living spaces in residential buildings in the respective standard.

Also investigation using dynamic building simulation software BSim was made, to evaluate if PCM application in the designed house would bring desired effect of decreasing energy consumption for heating and cooling. In total four cases were simulated, starting with the simplest conventional structure and at last having a structure which is fully packed with PCM:

- 50 mm PCM layer in direct contact with indoor space (green column)
- Embedded pipe system in wooden construction (blue column)
- 50 mm PCM layer covered with 10 mm plywood layer (orange column)

- 50 mm PCM layer on the ceiling, covered by 10 mm plywood layer and embedded pipe system in the wooden floor structure (violet column)

Only cooling season was investigated due to limitation of the software. Results of these simulations are presented in the following chapter.

7. Results

Presented results are mostly from simulations and the respective simulation software is indicated in the parentheses.

Simulation results for the designed ground heat exchanger are presented below:

Insert Table 3 here

Also long-term behavior of the ground has been investigated, results are presented in the below table and following figure:

Insert Table 4 here

Insert Figure 8 here

Presented results for PV/T system are obtained from calculations and simulations:

Insert Table 5 here

In order to evaluate the house on an all year round basis, also simulations have been carried out and the results of the simulations are presented in the following table:

Insert Table 6 here

The results of the dynamic simulation for the PCM application in the house are presented in the figure below (cooling season May-September):

Insert Figure 9 here

8. Discussion

The evaluations show that the house performs as a plus energy house on an annual basis however it should be kept in mind that the results are aggregated values over a year and the time of energy production and consumption doesn't necessarily correspond to each other.

For both of the locations, the highest contribution to the energy consumption is from the heating demand. This is mainly due to the North and South glass façades. This effect somewhat offsets the positive effect of the low U-value of the walls.

Embedded pipes in the floor and ceiling are advantageous in achieving the goal of energy efficient heating and cooling, mainly due to the high temperature cooling and low temperature heating concept enabling the natural resources to be integrated into the HVAC system, in this case being ground heat exchanger.

Free cooling is possible to observe for both of the locations, taking Madrid as an example, the same amount of cooling would have been delivered with 848 kWh of electricity compared to 65 kWh of electricity, if it were to be done with a representative chiller. For the heating case, long-term effects should be considered and kept in mind while realizing this design.

PV/T panels enable the house to be self-sufficient and even produce more energy than it consumes on the electrical side and PV/T panels also contribute significantly to the heat demand for the domestic hot water consumption.

The maximum thermal efficiency of the PV/T panel, with passive solar cells was measured as 48%, when the PV/T panel was cooled by water at 20°C. With active solar cells the maximum efficiency was decreased by 6% to 42%.

Even though the mechanical ventilation provides better control over the important comfort parameters, natural ventilation possibilities should be exploited until the limits in order to save energy.

The results from the BSim simulation proved that using thermal mass such as PCM decreases energy consumption for the cooling. The highest energy savings using PCM appear in early and late cooling season months, up to 30%. At the peak month energy consumption using PCM is lower, yet only approximately by 20%, compared to conventional water based cooling system.

9. Conclusion

The main goal of this study was to design the heating, cooling and ventilation system of DTU's house for the competition, Solar Decathlon Europe 2012 and to power it with photovoltaic/thermal panels however it was not limited to this extent. Further evaluations were carried out regarding different energy saving and energy efficiency mechanisms.

The competition rules regarding temperature, relative humidity and indoor air quality were on the focal point of the design however an all year round approach was utilized in order to assure that the house and its systems can perform as close as possible to optimum. Keeping these constraints in mind, the components and the HVAC system were designed, simulated and fortunately most of these components were tested and evaluated in full scale once the house was erected in Denmark and later during the competition in Madrid. During the competition period, it was observed that the designed system is capable of meeting the requirements regarding comfort conditions during most of the time [6].

One of the aims of the study was to develop a commercially available PV/T product because currently, the conditions of the PV/T market are very tentative. Many manufacturers promote a number of various combinations of different technologies, but they offer only the end-product which is not the key to sustain the proclaimed hybrid efficiency. A well designed combination of thermal and electrical part can ensure the proclaimed rise of effectiveness and let the PV/T technology to excel in the advantages compared to the conventional solutions.

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Tables- Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels

Table 1: House construction details

External walls	South	North	East	West	Floor	Ceiling
Area [m^2]	-	-	37.2	19.3	66.2	53
U-value [W/m^2-K]	-	-	0.09	0.09	0.09	0.09
Windows	South	North	East	West	Floor	Ceiling
Area [m^2]	21.8	36.7	-	-	-	0.74
U-value [W/m^2-K]	1.04	1.04	-	-	-	1.04
Solar transmission	0.3	0.3	-	-	-	0.3

Table 2: Active and no active cooling effect

	Efficiency [%]	Panel temperature [°C]	Air temperature [°C]	Solar irradiation [W/m^2]
Active cooling	15.5	32±0.5	22.5±0.5	880÷950
No Active cooling	13.5	66±0.5	22.5±0.5	880÷950

Table 3: Obtained results for both locations, annually (TRNSYS) [9]

	Copenhagen	Madrid
Heat Pump, heat to load	6932.3	4351.3
Energy balance, ground	-3128.8	-548.6
Free cooling total [kWh]	1301.1	2042.6
Free cooling to the house	1195.8	1661.0
Free cooling to the PV/T	105.3	381.6

Table 4: Initial and average temperatures and heat balance of the ground (TRNSYS) [9]

	Copenhagen	Madrid
Initial ground temperature [°C]	8.3	14.3
Average ground temperature [°C]	7.8	14.2
Heat balance of the ground [MWh]	-28.7	-2.8

Table 5: Obtained results for PV/T panels and DHW consumption, annual (calculations and TRNSYS) [5]

Unit	Variable	PV/T (heating mode)	PV	Solar thermal	PV/T - (PV+T)
%	Efficiency	15.34+36.6	13.59	42.8	
kWh/ year	Net annual el. en. balance; Copenhagen**	7434 + 242*	7214	259	+ 203 (2.6%)*

kWh/ year	Net annual el. en. balance; Madrid**	11393 + 495*	10970	530	+ 388 (3.3%)

*Heat transferred to electricity in a way, how much electricity would be used to charge the 180 l DHW to 60°C by a heat pump (COP 3.28 for heating)

**Solar fraction was obtained to be 62.7% for Madrid and 30.5% for Copenhagen, annually.

Table 6: Energy consumption by building need (TRNSYS) [9]

	Copenhagen	Madrid
Heating [kWh/m^2]	31.6	20.7
Cooling [kWh/m^2]	0.5	1.0
Ventilation [kWh/m^2]	0.7	5.2
DHW [kWh/m^2]	7.3	3.8
Rest of the electricity [kWh/m^2]	5.6	4.4
Total electricity consumption [kWh/m^2]	45.6	35.1
Total primary energy consumption [kWh/m^2]	114.1	105.2
Total energy balance (electricity) [kWh/m^2]	66.7	137.0

List of Figure Captions- Sustainable Heating, Cooling and Ventilation of a Plus Energy House via Photovoltaic/Thermal Panels

Figure 1: Bird's-eye view of the PV/T system, North-East and South-West sides of the house and the structural element [3]

Figure 2: Thermal efficiency and temperature fluctuation for two different spacing of lateral pipes [4]

Figure 3: The tested PV/T panel [5]

Figure 3: Thermal efficiency of the PV/T panel

Figure 4: Electrical scheme of the test setup [4]

Figure 5: Measured and idealized electrical efficiency of the PV/T panel [5]

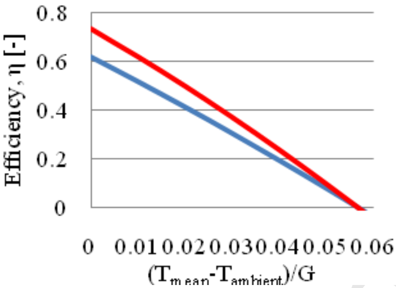
Figure 6: Hybrid efficiency of PV/T panel [4]

Figure 7: 10 year average ground temperatures for Copenhagen and Madrid (TRNSYS)

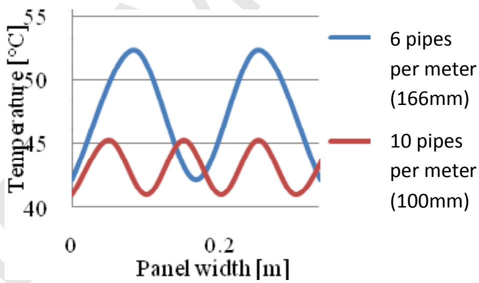
Figure 8: Energy consumption for cooling season in Madrid for different constructions (BSim) [10]

Figures - Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels

Figure 9: Bird's-eye view of the PV/T system, North-East and South-West sides of the house and the structural element [3]



Efficiency, η [-]
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
0.05
0.06
(T_mean-T_ambient)/G



Temperature [°C]
55
50
45
40
0
0.2
Panel width [m]
6 pipes per meter (166mm)
10 pipes per meter (100mm)

Figure 10: Thermal efficiency and temperature fluctuation for two different spacing of lateral pipes [4]

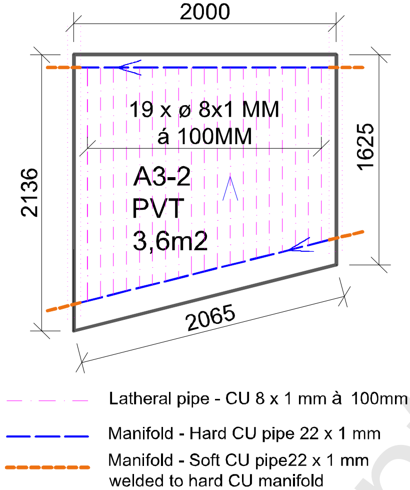


Figure 3: The tested PV/T panel [5]

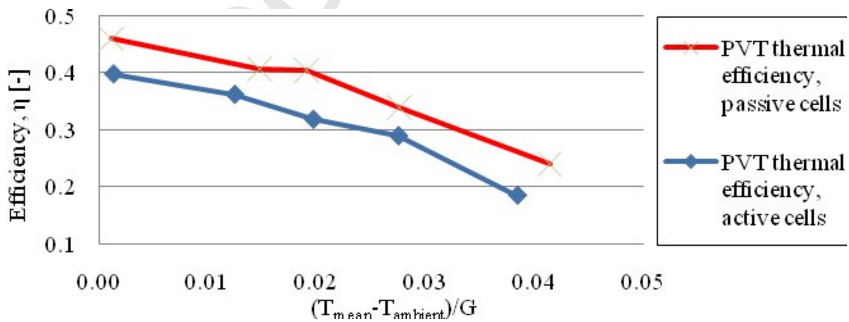


Figure 11: Thermal efficiency of the PV/T panel

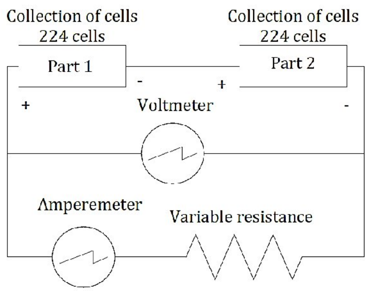


Figure 12: Electrical scheme of the test setup [4]

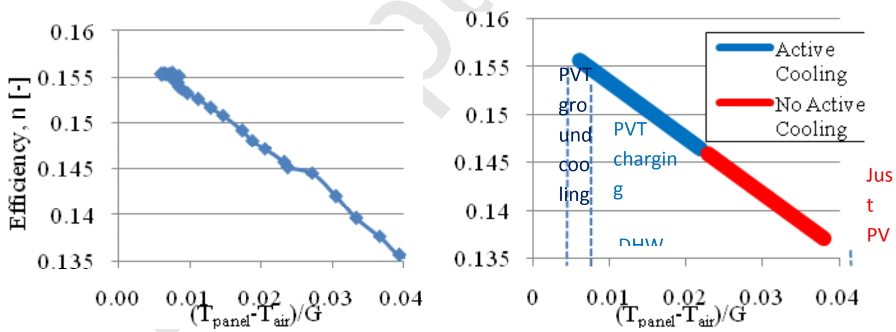


Figure 13: Measured and idealized electrical efficiency of the PV/T panel [5]

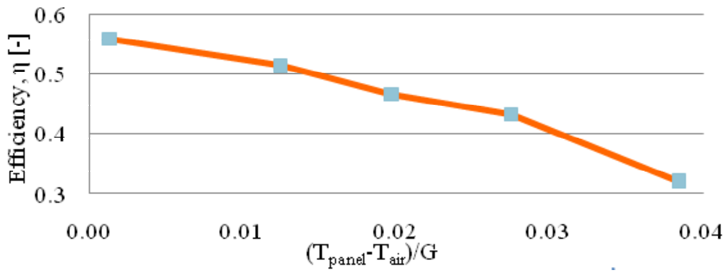


Figure 14: Hybrid efficiency of PV/T panel [4]

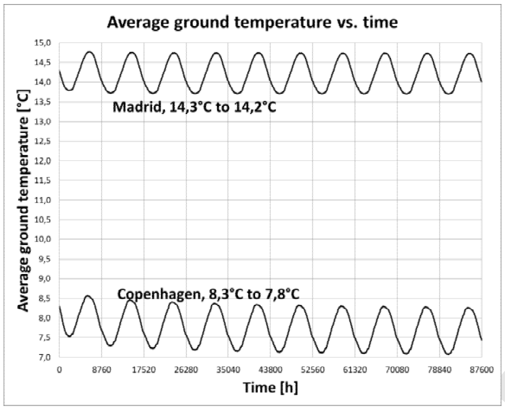


Figure 15: 10 year average ground temperatures for Copenhagen and Madrid (TRNSYS)

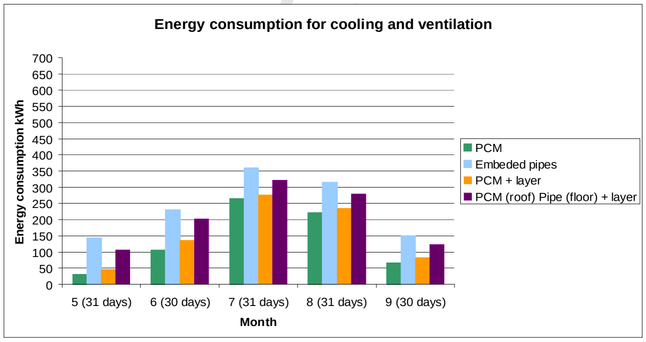


Figure 16: Energy consumption for cooling season in Madrid for different constructions (BSim) [10]

Use of PCM-Plasterboard Ceiling Panels for Building Thermal Mass Enhancement, Temperature Control and Peak Load Management in a Continental Mediterranean Climate

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Abstract

Ceiling-mounted cooling panels containing phase change material (PCM) are a promising solution for adding thermal mass in lightweight buildings and when retrofitting. In the present work the performance, in terms of thermal comfort and cooling load management, of PCM-plasterboard ceiling panels was evaluated in computer simulations using TRNSYS 17 for an office building. PCMs with different fusion temperatures, and a number of different night-time cooling principles were investigated. Results from the study show that PCMs with a fusion temperature close to the desired mean room temperature are the most beneficial in terms of temperature control. Efficient night-time cooling is important to allow solidification of the PCM material so that it is able to absorb excess heat in the following day. The concept proved capable of shifting a significant proportion of the space cooling loads to night-time and thus of reducing the peak cooling demand.

Keywords - PCM; TABS; thermal mass; ceiling cooling panels

1. Introduction

The building sector requires a substantial amount of the energy used in the European Union countries [1] and there has been increased interest in energy-efficient cooling concepts for commercial and office buildings. One approach for conditioning low-energy office buildings in summer is to effectively increase the thermal storage capacity of buildings by coupling them to low exergy heat sinks, e.g. ambient air or soil, which operate with small temperature differences to the room air.

An extensive survey of research on passive building thermal storage utilization, e.g. the pre-cooling of a building's thermal mass during night-time in order to shift and reduce peak cooling loads to reduce energy consumption in commercial buildings, was carried out [2][3][4]. In climates where the outdoor conditions are favourable (high diurnal ambient temperature variations, low outdoor air relative humidity), passive cooling techniques like natural or hybrid night-time ventilation can be exploited to remove excess heat and cool down the thermal mass of a building [5]. In climates with low diurnal ambient temperature variation and high outdoor air relative humidity, mechanical pre-cooling of the building during night-time can be used to reduce and delay peak cooling demand [6][7]. Load shifting reduces energy costs by making it possible to use the low cost off-peak electricity rates that are offered to reduce peak electricity demand, and to use this energy under more favourable ambient operating conditions.

Thermally activated building systems (TABS) use the various thermal capacities of the building structure as thermal energy storage and are thereby integrated in the overall energy strategy of the building [8][9][10]. Heat gains during the day are stored in solid floors and slabs, which are then re-cooled at an appropriate time by means of a water pipe system. The temperature of the cooling water can be close to desired room temperature, which means high potential for using renewable energy sources (ground source heat pumps, ground heat exchangers, etc.) [8][11][12].

Due to this active utilization of the thermal mass, cooling loads can be reduced and shifted to off-peak hours. There is no need to instantly supply the cooling demand of the space to the slabs; it can instead be transferred with a time shift and at power levels which may differ from the actual demand. Shifting of the daily cooling loads to night-time allows operation at a reduced night electricity price [13]. Additionally, the cooling system does not have to be designed to cover the maximum thermal load and the reduced capacity of the refrigeration equipment provides further economies.

The passive and active thermal mass activation concepts are inappropriate for lightweight buildings, such as frame buildings with no interior mass. In thermally heavy buildings, the building fabric provides the necessary thermal mass, but alternative solutions for lightweight buildings are required. Adding thermal mass to buildings as part of a retrofitting scheme is not easy because light buildings often cannot support the increase in weight.

Phase change materials (PCMs) have the potential for storing much larger amounts of thermal energy per unit mass or unit volume, compared to conventional building materials like bricks and concrete, by storing the thermal energy as latent rather than as sensible heat [14]. Latent storage in phase-change materials incorporated into building materials has become a main focus of current engineering research [15] [16] [17]. However, there are still many unanswered questions about the optimal incorporation of phase change materials in building materials and components, selecting the most suitable phase change temperature for each particular application, and integrating the storage capabilities of these materials into the overall energy and space conditioning strategies of the building.

The aim of the present work was to evaluate the use of phase change materials in building materials and components to enhance the thermal mass of buildings and to improve cooling load management in continental Mediterranean climate. The evaluation was performed in terms of summertime temperature control, cooling load peak reduction and the shifting of the daily cooling demand to night-time hours. Similar effects on heating performance and on energy use for heating were not considered.

2. Phase Change Materials in Building Materials and Components

PCMs absorb thermal energy when they change phase from solid to liquid (melting), and release the stored heat when the material changes phase from liquid to solid (solidification). The phase change typically occurs over a small temperature range around their melting point (fusion temperature) and as a result the material exhibits very little temperature change over this range. The amount of heat absorbed or released is called the latent heat of fusion. The fusion temperature and latent heat of fusion may vary considerably between different materials [14].

Paraffin waxes, due to their availability and easily adjustable phase change temperature, are seen as promising materials for use in building materials and components [15][16][17]. With the development of PCM microencapsulation [18], a significant breakthrough has been achieved in the incorporation of PCMs into building components such as gypsum boards, plasterboards, floor tiles, bricks, concrete, etc. [19]. However, cost issues related to the microencapsulation process represent a substantial barrier for the widespread adoption of these applications.

Plasterboard is the most widely used wall and ceiling lining material in lightweight buildings. Use of PCM-plasterboards instead of conventional plasterboards has the potential for increasing the thermal mass of lightweight buildings and can help to avoid overheating problems in such buildings. Phase change materials with fusion temperature close to the desired mean room temperature would provide effective thermal storage capacity, while the large surface area would enhance the heat transfer and respectively the efficient utilization of that distributed thermal mass.

Plasterboards with incorporated microencapsulated PCM, for thermal mass enhancement and room temperature control, have been studied experimentally and in numerical simulations [20][21][22]. The published results have shown their potential for decreasing indoor temperature variations, in comparison with conventional plasterboards. PCM melting temperature, amount of PCM used, and the permitted indoor temperature variation have been identified as the most important parameters influencing the efficient utilization of added thermal mass. The importance of night-time ventilation rates and supply temperatures for cooling efficiency has been emphasized for these passive thermal mass utilization principles [20][23].

In the past few years more experimental studies on PCM plasterboards have been documented [24][25][26]. In these studies it has been shown that gypsum can be combined with up to 45% by weight of PCM when the board structure is reinforced with some additives, and with up to 60% by weight in wallboard composites.

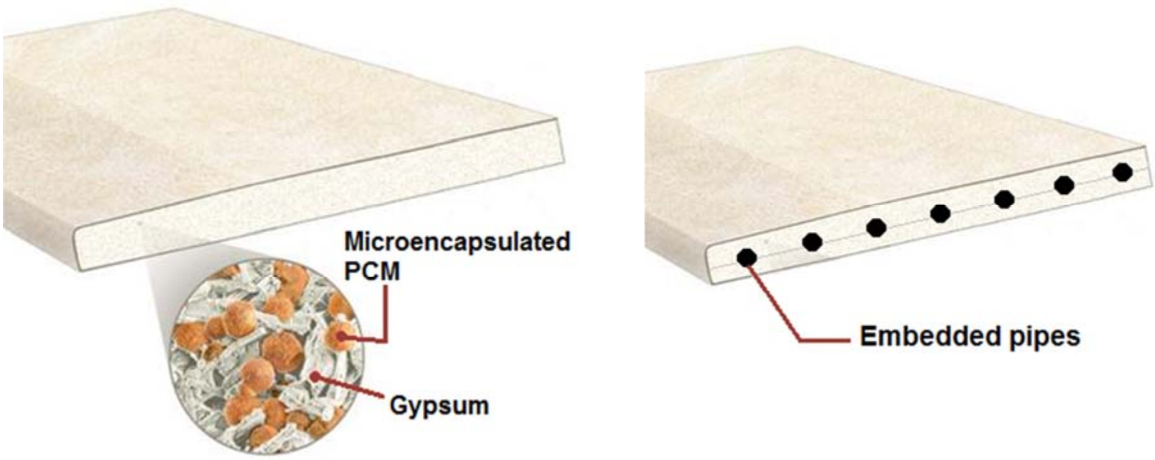
In addition to the passive thermal mass concepts there has been increased interest in ceiling mounted radiant cooling panels, where the PCM provides the necessary thermal mass and an embedded pipe system provides active discharging of the stored thermal energy [27][28]. In these applications, excess heat is stored in the PCM plasterboard during peak energy demand hours, and the stored thermal energy is later extracted from the building during off-peak electricity periods. This approach is known as a thermally activated building thermal mass utilization strategy for room temperature control and storage of thermal energy for cooling purposes.

As in the passive applications of PCMs, their melting temperature and the amount of PCM used would determine the indoor thermal conditions and the ability of the system to shift the cooling load. The active discharge strategy for the PCM storage through the embedded pipes system taps the full potential of the added thermal mass, making it independent of the outdoor climate conditions.

3. PCM-Plasterboard Panels for Suspended Ceiling Installations

PCM-plasterboard panels for suspended ceiling installations were considered in this paper as an application that offers high potential for increasing the thermal mass of lightweight buildings and for renovating existing buildings. A simple lightweight office building was considered, in order to assess the performance of the PCM-plasterboard suspended ceiling in cooling mode during summer, for a continental Mediterranean climate.

The ceiling panels were made of plasterboard combined with a microencapsulated paraffin wax material. Both passive ceiling panels combined with night-time natural ventilation and active ceiling panels with embedded pipes for night-time cooling were considered in the performance evaluation, Fig.1.



a) passive panel   b) active panel

Fig. 1 Plasterboard ceiling panels with microencapsulated Phase Change Material

In order to evaluate the potential benefits of the added thermal mass, the performance of the PCM-plasterboard ceiling panels was compared to conventional passive and active gypsum panels without added PCM. Additionally, the effects of PCM melting/solidification temperature and the night-time cooling principle were examined.

4. Methods

The performance of the PCM-plasterboard ceiling panels was evaluated using a simulation tool integrated into the numerical simulation environment TRNSYS 17 [29]. The tool, developed in [30], simulates the thermal behaviour of rooms in buildings with PCM in passive and active wall constructions.

4.1 Office Space and Building Envelope

A reference building model was developed in order to study the proposed concept of PCM-plasterboard ceiling panels. The indoor space simulated was a 2-person office room located on a middle floor in a multi-story building. The office space had a total floor area of 22.7 m^2 and a volume of 68.1 m^3. The only exterior wall was facing South, and had a glazed surface area of 4.5 m^2. The layout of the office is shown in Fig. 2.

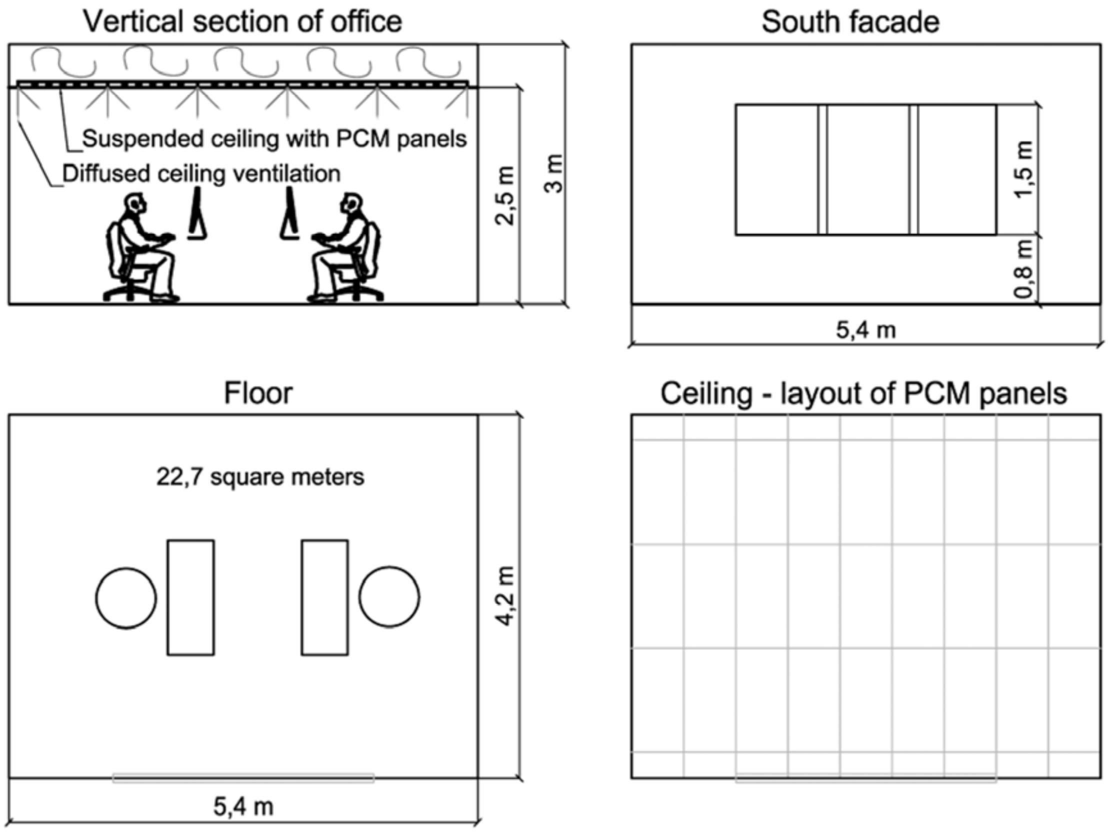


Fig. 2 Office Layout

Building envelope data is given in Table 1. The building had very low thermal mass; the exterior construction was built of highly insulated lightweight panels, and the interior walls were built of gypsum panels with acoustic insulation. The windows were equipped with external solar shading that gave an additional shading factor of 0.8, and was activated when the solar radiation on the window pane exceeded 300 W/m^2.

4.2 Internal Heat Gains

The internal heat gains in the office were assumed to be 23.4 W/m^2 (100% convective gains) and comprised 2 occupants, lighting and equipment. The loads were assumed to be 100% present during daily occupancy hours (9 a.m. - 5 p.m.).

Table 1. General information for the building

Building element	South wall (external)	Windows (South wall)
Area [m^2]	16.2	4.5
U-value [W/m^{2}K]	0.105	0.68
Solar transmission	-	0.4

4.3 HVAC Systems

The PCM ceiling panels provided the main cooling capacity of the HVAC system. Suspended ceiling installation were considered (Fig.2). The space created between the suspended ceiling and the structural slab of the building was used as a plenum, where the ventilation air was first supplied to the building and then directed into the office space through the gaps between the ceiling panels. The ventilation system, operated daily from 8 a.m. to 5 p.m., was used to provide fresh outdoor air, and as a supplementary cooling system for the PCM ceiling panels. The ventilation flowrate used was determined according to [31], for Category I of indoor air quality (in a low polluting office). The supply temperature of the ventilation air was selected depending on the melting temperature of the PCM material used in the panels.

Two strategies for discharging the thermal energy stored in the PCM-plasterboard ceiling panels were investigated. The first strategy, as in a conventional TABS system, was to discharge the ceiling panels through the embedded pipe system during night-time. For the second strategy, the ceiling panels worked as passive thermal mass and night-time natural ventilation was used to discharge the PCM panels. For both discharging principles, night-time cooling was assumed to be in operation only as long as the thermal energy stored in the PCM panels' was being discharged (until the PCM material was completely solidified, which was assumed to be the case when the temperature of the panels reached the lower boundary of the phase change material's melting temperature range).

The energy consumed for discharging the stored thermal energy in the suspended ceiling was not considered in the analyses. The amount of energy used, especially for the cases with active panels with embedded pipes, will depend to a large extend on the control algorithm implemented for night-time cooling, and optimizing that control algorithm was not part of the current study.

4.4 Phase Change Materials

Due to the passive management of the daily heat gains by the PCM-plasterboard ceiling panels, it is expected that the daily operative temperatures will drift within certain limits. The Category III thermal environmental temperature range of 22-27°C given in [31] was selected as the thermal comfort range for the present study. As a result, phase change materials with fusion temperature close to the desired mean room temperature were selected.

Table 2. Thermal properties of the PCM materials

Material	PCM23	PCM24	PCM26
Melting range [°C]	21-25	22-26	24-28
Crystallization temp. [°C]	23	24	26
Spec. latent heat [kJ/kg]	110	110	110
Density [kg/m^3]	780	780	780
Thermal conductivity [W/mK]	0.26	0.26	0.26

The microencapsulated paraffin selected for the study was BASF Micronal® PCM with a melting temperature of 23°C [18]. Data on the thermal properties of that PCM are given in Table 2. In order to evaluate the effect of melting temperature on the performance of the ceiling panels, the same thermal properties were assumed for PCM with melting temperatures of 24°C and 26°C.

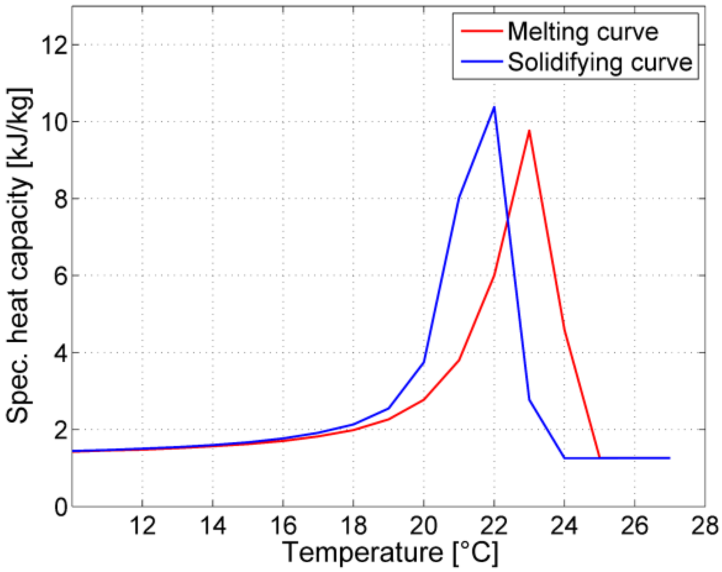


Fig. 3 Specific heat capacity of ceiling panels with P23 microencapsulated paraffin

Due to the incorporation of the microencapsulated PCM material in the plasterboard, data on the thermal properties of the composite PCM-plasterboard panel was required. Data for the simulations was obtained from [18] based on 25 mm thick plasterboard. The specific heat capacity as a function of temperature, for the ceiling panels with PCM23 microencapsulated paraffin is shown in Fig.3. The ceiling panels with PCM24 and PCM26 materials were assumed to have identical thermal properties, except that the melting and solidification curves are shifted to higher temperature ranges.

The study was based on an incorporation of 27% of microencapsulated PCM in mass content, providing 845 kJ/m^2 (235 Wh/m^2) heat of fusion.

4.5 Simulation Case Studies Description

Considering the variations in HVAC system configurations and PCM materials melting temperatures discussed above, several case studies were established. A detailed description of these simulation case studies is given in Table 3. In the following sections, the abbreviations SC and VSC will be used to denote conventional gypsum panels with and without embedded pipes, while P23 and VP23 will denote active and passive ceiling panels with PCM23 material. Similar acronyms follow for panels with PCM24 and PCM26 materials.

Table 3. Case studies description

Panels type (Case study ID)	VSC	VP23	VP24	VP26	SC	P23	P24	P26
PCM material	-	P23	P24	P26	-	P23	P24	P26
Day ventilation flowrate [h^{-1}]	2							
Supply air temp. [°C]	19							
PCM discharge	Nighttime ventilation				Night embedded pipes			
Discharge period	22 – 06				24 – 05			
Water flowrate (kg/h/m^2)	-				8			
Supply water temp. [°C]	-				18	18	18	18
Night ventilation flowrate [h^{-1}]	4				-			
Night supply air temp. [°C]	Outdoor air				-			

4.6 Meteorological Boundary Conditions

The meteorological ambient boundary conditions that were assumed corresponded to the hot continental Mediterranean climate of Madrid (Spain). IWEC weather data file was used for the simulations [32]. Typical outdoor daily temperature variations for the period investigated are given in Table 4.

Table 4. Meteorological data

Month	May	Jun	Jul	Aug	Sep	Year
Average high °C	21.4	26.9	31.2	30.7	26.0	19.4
Daily mean °C	16.1	21.0	24.8	24.5	20.5	14.6
Average low °C (°F)	10.7	15.1	18.4	18.2	15.0	9.7

5. Results

5.1 System Operation in Terms of Temperature Control

To evaluate the performance, in terms of temperature control, of the ceiling panels for the different system configurations, the indoor operative temperature achieved was selected as the evaluation parameter. In Figs.4 and 5 the operative temperatures indoors are shown, for suspended ceiling with night-time ventilative cooling and embedded pipes for night-time cooling, respectively. The temperature variations shown would occur during a typical summer week in July.

From the results for night-time ventilative cooling, it is seen that this cooling strategy is not appropriate for the location of Madrid, due to the outdoor temperature. The outdoor temperature was not sufficiently low for sufficiently long periods of the night to be able to cool the PCM panels below the solidifying temperature, and as on the following day the PCM material was still mostly melted, no phase change could occur and the panels were not able to absorb latent heat (excess heat). This led to overheating of the building. This phenomenon is particularly visible for the cases with ceiling panels VP23 and VP24 which, as they did not utilize the PCM, performed like conventional gypsum panels VSC. As a result of their high melting temperature range, the storage capacity of the ceiling panels VP26 was partly utilized during the day-night cycle, but still not enough to provide enough cooling in the space. However, the shift towards lower operative temperatures was clear, and a certain effect of the thermal mass could be observed.

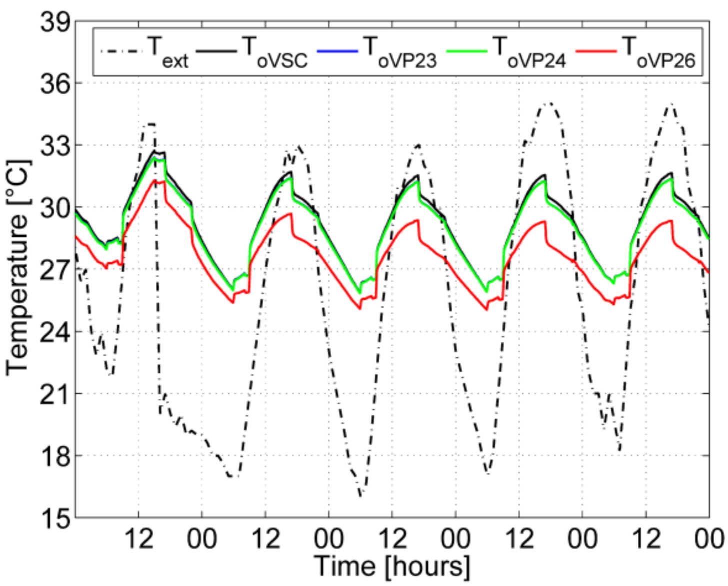


Fig. 4 Operative temperatures – nighttime ventilative cooling

A completely different result was obtained for the night-time cooling strategy using embedded pipes, where due to the use of heat carrier fluid circulating in the embedded pipes, the heat storage and release process in the ceiling PCM panels could be intensified and to some extent controlled. The panels were completely discharged during the night, and their whole storage capacity was available for cooling during the following day.

The results show that for the case studies of ceiling panels P24 and P23 the operative indoor temperatures were within the specified comfort limits (22 – 27°C) during the hours of occupancy (8 a.m. – 5 p.m.). The highest daily operative temperatures occurred with ceiling panels P26 and with conventional gypsum radiant ceiling panels SC. The results show that the indoor operative temperature range was directly dependent on the PCM melting temperature: the lower this temperature, the lower the operative temperature indoors. The effect of added thermal mass was clearly shown by the dampened amplitude of the daily variation in the operative temperature in the cases with ceiling panels with PCM compared to the conventional gypsum panels. The PCM melting temperature had a negligible effect on the amplitude of the daily variation of the operative temperature.

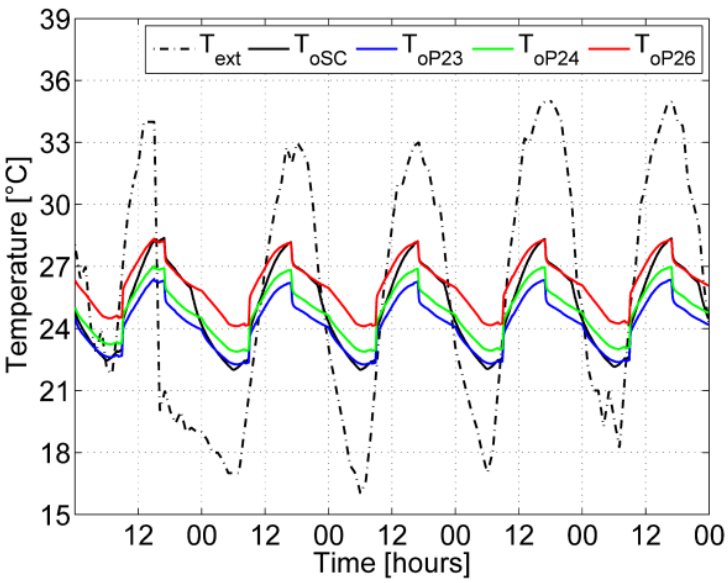


Fig. 5 Operative temperatures – nighttime embedded pipes cooling

Further investigations of the temperature control capabilities of the ceiling panels with PCM were carried out using the seasonal temperature duration curves given in Figs.6 and 7 for the cases with night-time ventilative cooling and embedded pipes for night-time cooling, respectively. The duration curves show the number of hours the operative temperature was at each temperature level, and encompass the summer (cooling) period May-September for the given climatic location.

As also it was shown from the previously shown results on operative temperature variation, the night-time ventilative cooling principle was not a very efficient concept for the climate of Madrid. For all simulation case studies, there were many hours with indoor operative temperatures above the limit of 27°C (overheating), which was the upper comfort limit for this study (Category II [7]).

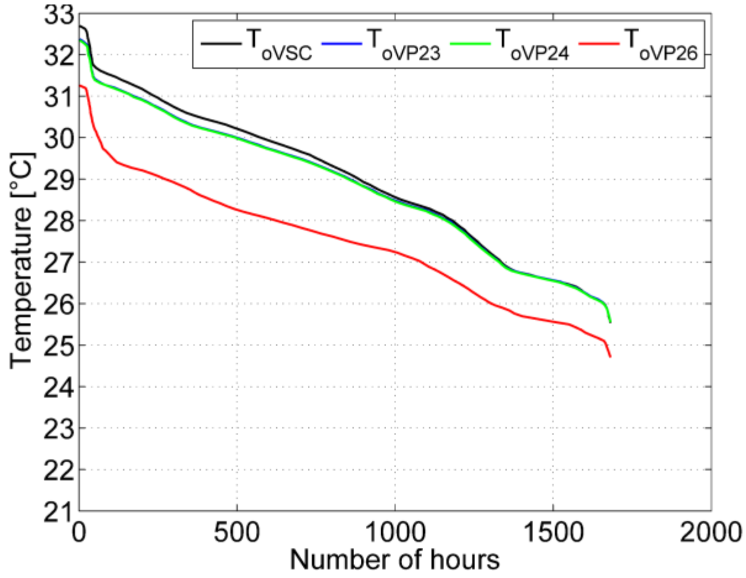


Fig. 6 Operative temperature duration curves – night-time ventilative cooling

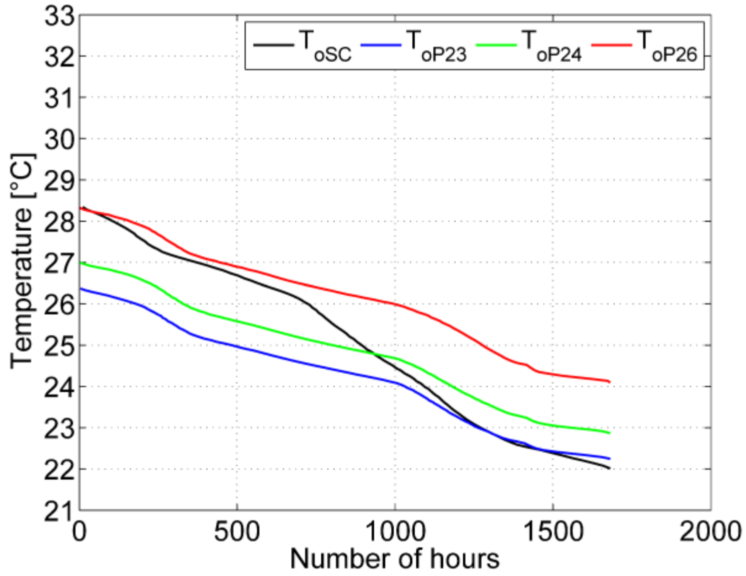


Fig. 7 Operative temperature duration curves –embedded pipes for night-time cooling

For the embedded pipes cooling principle, much more promising results were obtained. Depending on the PCM melting temperature range, different indoor thermal comfort was achieved, e.g. for the ceiling panels P23 the indoor operative temperature varied between 22.3 and 26.3°C during the summer months. When PCM with a higher melting temperature was used in the panels, higher operative temperatures indoors occurred. The effect of the thermal mass added by the PCM could be seen by comparison with the indoor temperature variation range obtained with conventional gypsum. Much lower temperature variations resulted for the cases with PCM panels, i.e. conventional gypsum panels SC: 22-28.2°C vs. PCM ceiling panels: P23 between 22.3-26.3°C, P24 between 22.9-27°C, and P26 between 24.1-28.2°C.

5.2 Thermal Energy Storage and Cooling Load Management

In this section, results on thermal mass enhancement, load shifting and peak load cutting are presented. The analyses were performed for a typical summer day in July.

Since the main objective for the ceiling cooling system was to store the excess heat gains in daytime in the PCM ceiling panels for subsequent night-time extraction, the energy stored and discharged in a 24-hour cycle may be used as one of the main system performance evaluation criteria. In Figs.8 and 9, the internal and solar heat gains in the office space are shown, and compared to the thermal energy stored in the ceiling panels and the supplementary cooling provided by the ventilation system during daytime, for a typical summer day in July, from 8 to 17.

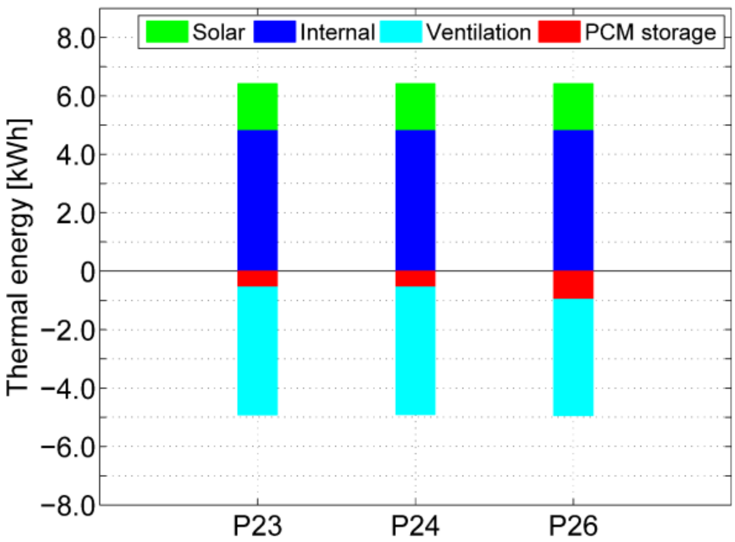


Fig. 8 Thermal loads and stored energy during the day – night-time ventilative cooling

As noted above, when the night-time natural ventilative cooling principle was used, very little of the PCM panels storage capacity was utilized, as the indoor operative temperatures were higher than the melting temperatures of the PCM materials. Most of the cooling in the daytime was provided by the ventilation system, and almost none of the cooling demand was shifted to night-time hours. As a result, many hours with overheating were encountered. Due to the proven unsuitability of the night-time natural ventilation as a cooling strategy for the given climatic conditions, further results on thermal mass enhancement and cooling load management for the different ceiling panels' systems will be presented only for the embedded pipes cooling principle.

When embedded pipes were present, the thermal mass of the PCM panels was much more efficiently utilized. To evaluate the amount of storage capacity utilized, the maximum storage capacity of the ceiling panels, equal to 5.3 kWh of thermal energy, was compared with the actual amount of stored energy.

For P23 panels, about 78% (4.1 kWh) of the storage capacity was utilized during daytime, and this utilization dropped to about 74% (3.9 kWh) for P24 and to 62% (3.3 kWh) for P26. The stored thermal energy represents the cooling load shifted to night-time by the increased thermal mass of the building.

These results illustrate the importance of complete cycling of the state of the PCM material from solid to liquid and back to solid in a 24h daily cycle, for the efficient utilization of the added thermal mass. That complete cycling of the state of the PCM material depends on the melting temperature range of that material, on the indoor temperature variation during daytime storage of excess heat, and on the complete discharging of the stored thermal energy in the ceiling panels during night-time. The results show that a lower melting temperature of the PCM resulted in more excess heat stored and more cooling load shifted to night-time hours, and that for the climate of Madrid, embedded pipe cooling was more efficient compared to night-time natural ventilation.

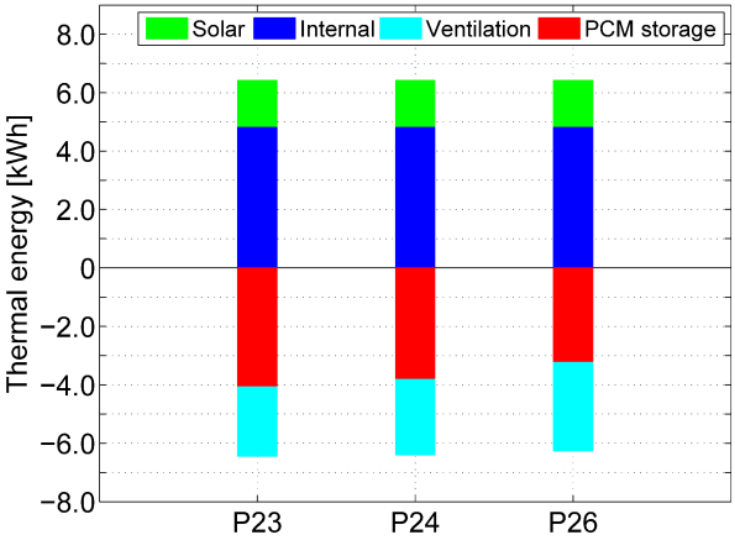


Fig. 9 Thermal loads and stored energy during the day – nighttime embedded pipes cooling

Storing the excess heat in the thermal mass of the ceiling panels reduced the need to actively cool the space. That cooling load was transferred to night-time at lower power levels. The peak load shaving effect was evaluated by comparing the intensity of the cooling load stored in the ceiling panels during daytime, and the power required for the mechanical cooling that was performed at night in the embedded pipes system.

In Fig.10, the cooling power provided by the PCM ceiling panels is shown during hours of occupancy. If the cooling had to be provided immediately by a mechanical cooling system, it would mean that the mechanical system would have to be sized for that cooling power. In Table 5, the peak load shaving capability of the PCM ceiling panels is given, by comparing the cooling power needed by the embedded pipe system during night-time discharge of the stored thermal energy, and the cooling power needed if immediate mechanical cooling was used during the day.

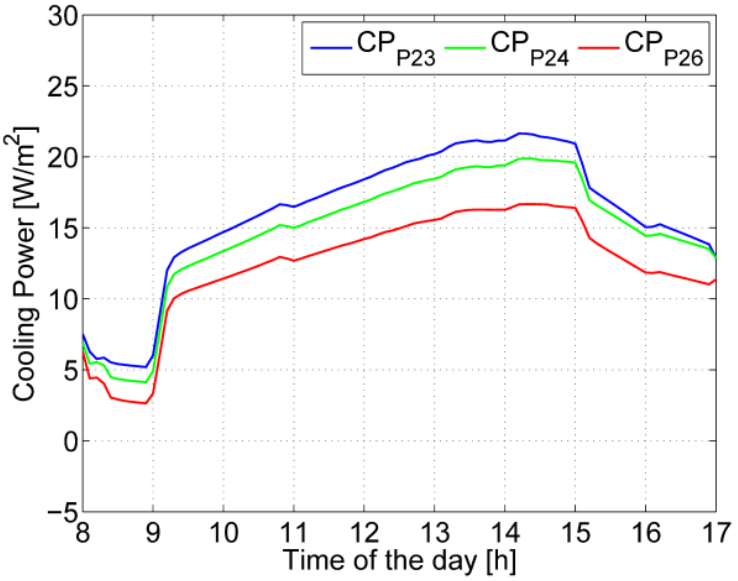


Fig. 10 Cooling power – nighttime embedded pipes cooling

The estimated peak load shaving indicates that using ceiling panels P23 provided a 50% reduction in the peak cooling load, while the P24 panels provided a 35% reduction and the system with P26 panels provided only an 11% decrease in peak demand.

Table 5. Cooling power and peak load shaving

Ceiling panels type	Intermittent mechanical cooling [W/m^2]	Nighttime embedded pipes cooling [W/m^2]	Peak load decrease [%]
P23	22.1	11.1	50
P24	20.2	13.1	35
P26	17.1	15.3	11

6. Discussion

The results show that efficient night-time cooling is important to allow cooling and solidification of the PCM material in the ceiling panels, so that it is able to absorb excess heat the following day. Night-time ventilative cooling would not be an efficient strategy in warm and hot climates like Madrid. Use of embedded pipes for night-time cooling was necessary for the efficient utilization of the thermal mass added by the PCM.

The simulations showed that active PCM-plasterboard panels with microencapsulated paraffin with fusion temperatures of 23°C (range 21-25°C) and 24°C (range 22-26°C) performed best in terms of temperature control, for the conditions studied. These temperatures were around the mid-point of the chosen comfort range of 22-27°C indoor operative temperature. The peak indoor operative temperatures were decreased by 2-3°C, and the hours of overheating were eliminated, compared to the use of conventional gypsum ceiling panels.

The observed behaviour of the PCM-plasterboard ceiling panels was compared with results obtained in previous studies [23][28], where it was also shown that PCMs with melting temperatures close to the mid-point of the desired indoor temperature range are most efficient in terms of temperature control, and that PCMs with a melting temperature range shifted towards the lower boundary of the desired indoor temperature variation range would be the most beneficial.

In terms of thermal storage capacity utilization, cooling load shifting and peak reduction, PCMs with fusion temperatures of 23°C and 24°C were very effective. Load shifting to night-time of 78% and 74%, and peak cooling load reduction of 50% and 35% respectively, were obtained.

Regardless of the observed benefits, it must be carefully considered under which conditions the proposed thermal mass enhancement concept would result in significant energy and cost savings

Load shifting to night-time is most beneficial if night-time natural ventilation can be used for cooling, or if day-night and peak demand electricity tariffs exist. Peak load shifting, on the other side, is beneficial when peak demand electricity pricing is present, and could be an efficient means of downsizing the refrigeration plant.

Due to the high price of microencapsulated PCMs, the justification for their use in buildings must be based on a detailed cost analysis. The potential savings due to off-peak electricity use, the downsizing of refrigeration equipment, and the space saved in buildings due to that downsizing will often compensate for the high investment costs associated with the use of PCM materials.

7. Conclusions

In the present work, ceiling cooling panels with PCM were investigated as an alternative thermal mass system for lightweight buildings and retrofitting. Their performance, in relation to thermal comfort and cooling load management, was evaluated. The optimum phase-change temperature range of the PCM material should be determined, so that the ceiling panel system will prove efficient in matching thermal energy availability and demand and in maintaining the desired indoor operative temperature. Use of PCMs with their melting temperature range shifted towards the lower boundary of the desired indoor temperature variation range was shown to be more beneficial.

The study showed the importance of efficient night cooling that allows solidification of all of the PCM material so that it is able to absorb excess heat the following day.

Overall, it may be concluded that the use of PCM plasterboard offers significant benefits for thermal mass enhancement in lightweight buildings and retrofitting. However, in each case, a detailed cost-benefit analysis must be performed to justify the use such an expensive solution.

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Simulation and optimisation of a ground source heat pump with different ground heat exchanger configurations for a single-family residential house

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SUMMARY
In the future there will be an increased demand for energy efficient cooling of residential buildings. Therefore it is essential to develop cooling concepts that are passive and/or using very little primary energy. A possible solution is a ground source heat pump combined with a low-temperature heating and high-temperature cooling system.
The present work evaluates the performance in relation to thermal comfort and energy consumption of a GSHP with different GHE concepts. The different configurations are analyzed being part of the energy supply system of a low-energy residential house, replicated for the climatic location of Copenhagen, Denmark.
The study results show no significant difference in systems' COP values during the heating season. During the cooling season the systems with VGHEs and sub-slab GHEs have shown up to 50% higher COP values, compared to systems with HGHEs. For the studied geographical location, passive cooling by bypassing the heat pump and using only the ground heat exchanger can provide acceptable room temperatures.

KEYWORDS
floor heating/ cooling; low energy homes; renewable technologies; indoor climate; simulation

1 INTRODUCTION

Since the mid 90s low energy buildings with significantly reduced energy consumption down to ultra-low energy standard (space heating energy need of 15 kWh/m^2/year) or even net zero energy consumption (on annual basis by integration of on-site renewable energy systems) have been realised. This has been made possible by better insulated and more airtight building envelopes, balanced ventilation systems with heat recovery and utilization of passive solar heating. On the contrary, due to the increased levels of insulation, air tightness, and demands for comfort, the need for energy efficient cooling has arisen. Therefore it is essential to develop heating/cooling concepts that are passive and/or using very little primary energy.
Due to their high energy efficiency, ground source heat pumps (GSHP) have been under extensive research as a heating/cooling source within the concepts for low and net-zero energy residential houses (Hamada et al., 2000; Sakellari et al., 2004; IEA HPP-AN32-1, 2011; Stene, 2008; Liu, 2008). An increase of the performance factor of these systems, compared to other types of heat pumps, is obtained by using the ground as a heat source with more moderate and balanced temperatures compared to ambient.
Heat to/from a conventional GSHP is extracted/rejected from/to the ground via a ground heat exchanger (GHE). The type of GHE used will affect heat pump system performance, auxiliary pumping energy requirements, and installation costs. There are two main types of GHE designs used in residential houses, vertical and horizontal. One more design alternative has been investigated in current research, sub-slab earth coupling (hydronic pipes embedded in a concrete slab below the building) (Rittelmann, 2007).

The aim of the present work is to evaluate and compare the performance in relation to thermal comfort and energy consumption of different GSHP/GHE concepts (with vertical, horizontal, or sub-slab GHE) through computer simulations using TRNSYS 17 (Klein et al, 2009). The different configurations analyzed being part of the energy supply system of a 110m^2 low-energy residential house, replicated for the climatic location of Copenhagen, Denmark.

2 BACKGROUND

In low energy and passive houses a heat pump system can be used to cover the entire heating and cooling demand. GSHPs obtain geothermal heat using a GHE. In the present paper, three different GHE designs (vertical (VGHE), horizontal (HGHE), and sub-slab GHE; Figure 1) are investigated and their performance is compared in terms of energy efficiency.

Figure 1. Ground-coupled (closed-loop) systems

The type of GHE used will affect heat pump system performance, auxiliary pumping energy requirements, and installation costs. Choice of the most appropriate type of GHE for a site is usually a function of available land area, energy performance and life cycle cost economics.
VGHEs make use of underground temperature stability which helps maintain a satisfactory COP value of the GSHP, unlike HGHEs in which, due to the shallow installation depths, the performances are directly related to local climatic conditions. However, it should be pointed out that the cost of boreholes represents the major drawback of the system.
A sub-slab GHE installed in a concrete slab below the building represents a new concept, which has significantly lower investment cost compared to systems with vertical GHE. Compared to horizontal GHEs, the need for excavation is eliminated, which is a major cost and construction barrier for horizontal ground coupled systems.

3 CASE STUDY DESCRIPTION

A reference model was developed in order to study the interaction between the building, the HVAC system and the controls. The analyses concentrate on the energy performance of the system using different GHE configurations. The simulations were performed with the aid of the dynamic simulation program TRNSYS 17.

Building envelope

A 110 m^2 one storey single-family residential house has been chosen for this study. The building envelope is well insulated and windows are of triple glazed low energy type. Due to the fact that the different rooms in the building have different energy requirements, the space is divided in eight distinctive zones. In Table 1 is given general building information.
The house is equipped with a mechanical ventilation system with heat recovery, supplying outdoor air in bedrooms and main living area. Exhausts are located in kitchen, bathrooms and utility room. The ventilation rate varies between the different zones. However the supply air temperature is the same for all the zones, controlled to a minimum of 17°C during the heating season and a maximum of 22°C during the cooling season.
In order to reduce peak cooling loads during summertime, the windows are provided with external shading that is controlled from the zone temperature. When the zone operative temperature exceeds 23°C, external shading (0.5 shading coeff.) is applied on the windows.

Table 1. General information for the building.

Building		Walls		Roof	Ground slab			Windows
Area, m^2		133.3		110	110			24.2
U-value, W/m^2K		0.077		0.075	0.052			0.59 (g-value 0.584)
Zones	V1	V2	V3	SV	BR	B1	B2	KA
Type	bedroom	bedroom	office	Bedroom	utilities	bath	bath	kitchen/living room
Orientation	SE	NE	N	NW	N	N	E	SW
Area, m^2	11	12.4	6.6	14.4	7.4	6.2	3	49
Volume, m^3	26.1	29.4	15.6	34.1	17.5	14.7	7.1	116.1
Vent, $l/s/m^2$ (ventilation rates according to Category II of EN 15251:2007)								
supply	0.4	0.4	0.4	0.4				0.4
exhaust					0.53	0.53	0.53	0.59
Occupancy load schedule, W/m^2								
6 – 8	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
8 – 17	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
17 – 23	9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9
23 – 6	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2

Floor heating and cooling system

Floor heating and cooling system is installed in the building. The system is of type A, Figure 2 (EN 1264, EN 15377), with pipes embedded in the screed. Each zone has a separate loop, consisting of 13 mm internal diameter PEX pipes, at a spacing of 15 cm.

The system is designed to supply a total water mass flowrate of 400 kg/h, which is divided to the individual rooms according to the maximum design heating/cooling loads of each zone. The control of the floor heating and cooling system is split up in a central control and an individual room control. The central control (Figure 2) will, according to the outside climate, regulate the supply water temperature to the floor system. The room control will then control the water flow rate individually for each room, according to the set-point room temperature. For the heating season operative room temperature set point of 21°C ±1K and for the cooling season operative room temperature set point of 25°C ±1K are selected, according to the recommendations for thermal environment Class II of EN 15251(2007).

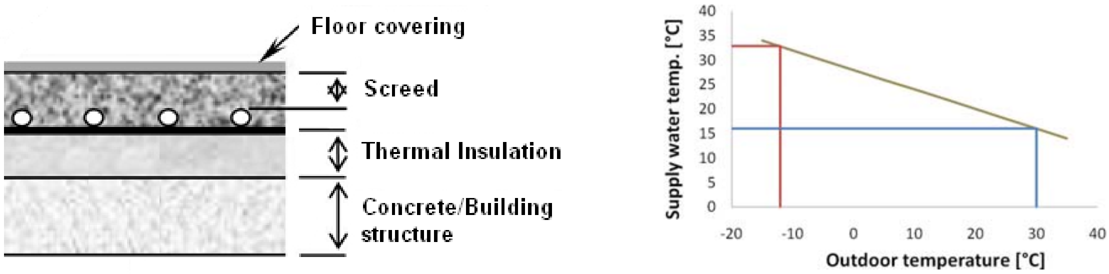

Figure 2. Floor structure Type A and Heating/Cooling curve for supply water temperature

Ground Source Heat Pump System

The heat pump is a water-to-water type with a nominal output capacity of 1.5 kW. Catalogue performance data in Figure 3 illustrate the range in efficiency with respect to inlet load and source water temperatures. The heat pump is controlled with an aquastat in order to deliver the required supply water temperature for the floor heating and cooling system with a deadband of ±1K. For the cooling season a passive cooling mode is given priority, in which the heat pump is bypassed and the supply water temperature is conditioned, through a heat exchanger, by the cool fluid circulating in the GHE. When the capacity of the GHE is not sufficient to provide the required water temperature, the heat pump starts operation.

The main parameters of the three different GHE designs (vertical, horizontal, and sub-slab GHE), as well as material properties of the soil and concrete slab are listed in Table 2.

Boundary conditions

The meteorological ambient boundary conditions correspond to Copenhagen (Denmark). The external temperature data for winter and summer design days are -12°C and 30°C. Summer period is from 1 May to 30 September, and winter period from 1 October to 30 April.

Ground heat exchanger configurations – Case studies

In order to evaluate the performance in relation to energy consumption of the different GSHP/GHE concepts, the following GHE configurations were studied, Table 4.

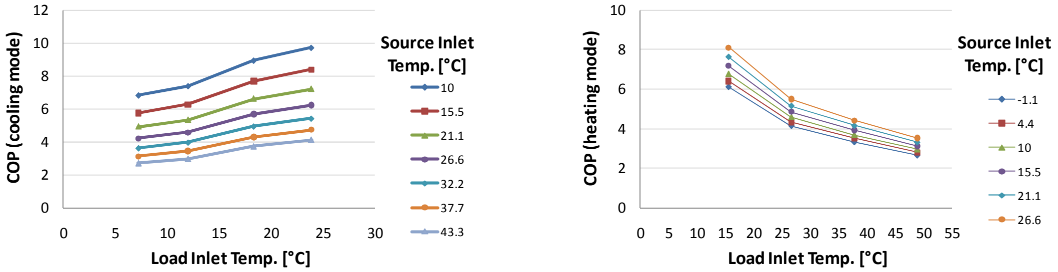

Figure 3. Heat pump efficiency - heating (right) & cooling mode (left)

Table 2. Ground heat exchanger, soil and concrete slab parameters

	VGHE	HGHE	Sub-slab GHE
Pipe inside (outside) diameter, m	0.013 (0.016)	0.027 (0.032)	0.027 (0.032)
Pipe thermal conductivity, kJ/h.m.K	1.44	1.44	1.44
Fluid thermal conductivity, kJ/h.m.K	2.066	2.066	2.066
Fluid specific heat, kJ/kg.K	4.19	4.19	4.19
Fluid density, kg/m^3	1000	1000	1000
Slab density, kg/m^3	-	-	2400
Slab conductivity, kJ/h.m.K	-	-	8.722
Slab specific heat, kJ/kg.K	-	-	1.0
Slab thickness, m	-	-	0.18
Soil density, kg/m^3	2400	2400	2400
Soil conductivity, kJ/h.m.K	6.3	6.3	6.3
Soil specific heat, kJ/kg.K	0.84	0.84	0.84

Table 4. Ground heat exchanger configurations.

Type of GHE	VGHE		HGHE – single layer, serpentine layout	HGHE – double layer, serpentine layout	Sub-slab GHE
Borehole depth or pipe length [m]	45	70	250 (12pipes x 20m)	150 (6pipes x 12m)	250 (14pipes x 17m)
Pipe space [m]	-	-	0.5	0.5	0.15
Layer depth [m]	-	-	1/-	0.5/1	-
Case #	Case 1	Case 2	Case 3	Case 4	Case 5

4 RESULTS AND DISCUSSION

Building heating and cooling demand

Simulation results showing the heating and cooling demand on monthly basis are given in Figure 5.The demands per m^2 floor area are 15 kWh/m^2/year for heating and 9 kWh/m^2/year for cooling. The peak heating load was 1.16 kW and the peak cooling load was 1.33 kW.

Heat pump COP and system COP

Simulation results for monthly average heat pump and system COPs for the different GHE concepts are shown in Figure 6 (heat pump COP is the energy output divided by the energy input of the compressor; system COP includes also the energy input of circulating pumps).

The GSHP with VGHE systems have shown about 5% higher system COP values compared to HGHE and sub-slag GHE systems. The slightly higher performance of VGHE systems is expected due to the more favourable deep ground conditions compared to the shallow installation depths of the other two types of GHEs.
An explanation for the similarity in performance of the different systems could be the required relatively low supply water temperature for the floor heating system, which has been within the range of 25-30°C during most of the heating season.
During the cooling season, the performance of the systems with VGHEs is clearly better compared to systems with HGHEs. In Figure 7 are shown monthly average system COP values when passive cooling and cooling using the heat pump were used. In addition the monthly energy delivered by the two cooling modes of operation (active-dark and passive-light colours) is shown. It can be seen that during the milder months of May and September the different systems have shown similar performance. During that period about 65% of the cooling needs were covered by passive cooling. During the peak summer months of June, July and August, the systems with HGHEs had lack of capacity, having about 50%-20%-5% (June-July-Aug) of the cooling needs covered by passive cooling. On the contrary, systems with VGHEs and sub-slab GHEs have delivered about 65%-80%-80% (June-July-Aug) of the energy demand for cooling by passive means.

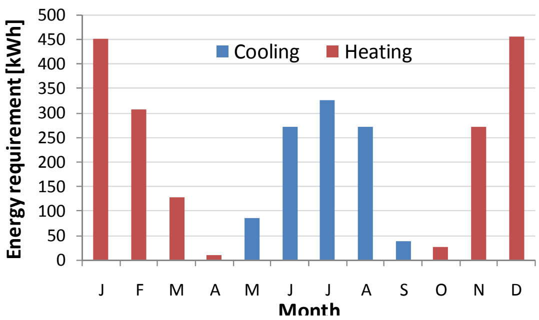

Figure 5. Residential house heating and cooling demands on monthly basis

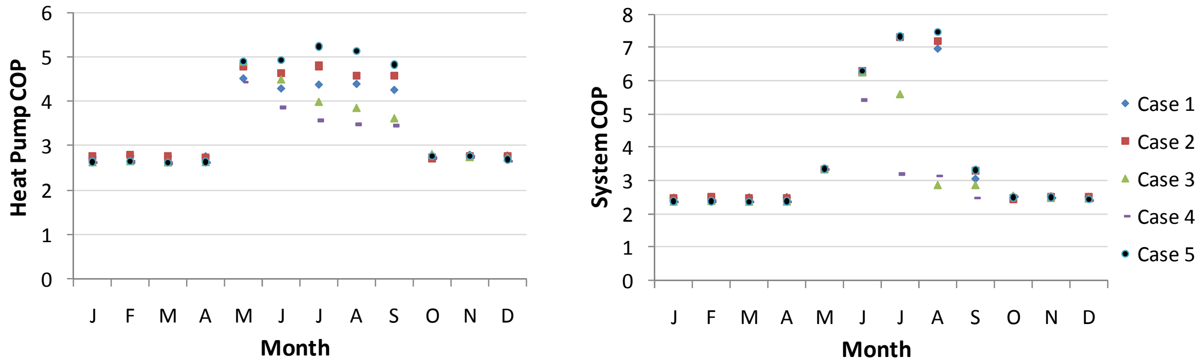

Figure 6. Heat pump COP and System COP for the studied GHE configurations

Interesting result is that the sub-slab GHE system has shown performance similar to the VGHE systems. From one side, it could be expected that the performance of that type of GHE will be similar to the HGHE due to same shallow installation depths. From another side, due to the fact that the sub-slab GHE is located below the house ground slab, some reduction of thermal loads due to direct solar radiation might have occurred. The effect of the thermally heavy concrete bed of sub-slab GHE should not be disregarded as well.
It should be noted that the average temperature in the concrete slab of the GHE varied between 8-17°C during summertime, compared to average ground temperature variation at a depth of 1m between 11-22°C. Additionally the required supply water temperature for the

floor cooling system during summertime of about 17.5-23.5°C (min - max values) and the low water and heat transfer fluid flowrates in the GHE and floor cooling system loops are factors that have increased the performance of the sub-slab GHE.

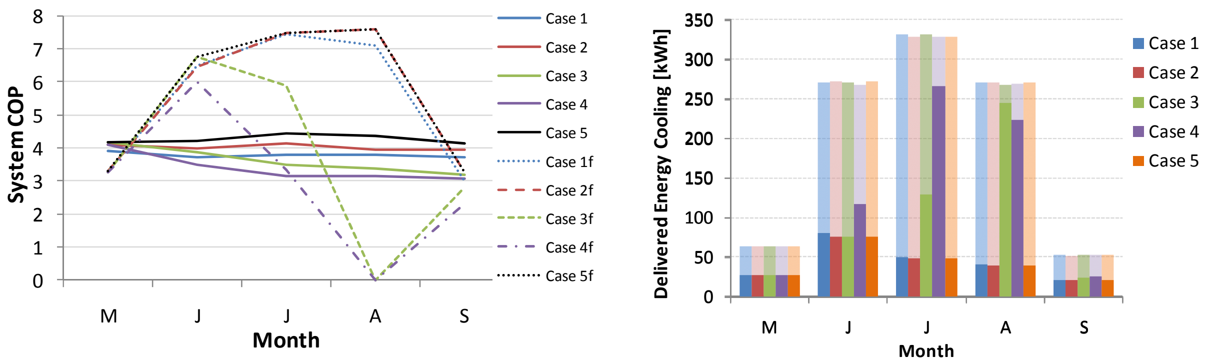

Figure 7. Passive/active cooling system COP and delivered energy comparison

6 CONCLUSIONS

In the present paper, a computer simulation study of a GSHP system, with different GHE configurations, has been done being part of the energy supply system of a low-energy house.
Results show that there is no significant difference between the performance of the different systems during the heating season. During the cooling season the systems with vertical and sub-slab GHEs showed up to 50% higher system COP values, compared to systems with HGHEs. It has been noted also that for the studied geographical location of Copenhagen, passive cooling can provide acceptable room temperatures during long periods of the summer, covering 20-80% of the total cooling demand, depending on GHE system configuration.
Results for the sub-slab GHE system, during the cooling season, showed performances comparable with systems with VGHEs. The much lower construction costs for such systems could open wide field of application for sub-slab GHEs. However, further investigation on the concept is required, including studies on the slab-soil interaction for different soil types and ground water flows. Additionally, the applicability of the concept at different climatic conditions and operating temperatures of the energy supply system on demand side should be evaluated and compared to VGHE and HGHE designs.

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INNO-S-20

Ground source heat pump combined with thermo-active building system with incorporated PCM for low-energy residential house

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1. Introduction

Since the mid 90's low energy buildings with significantly reduced energy consumption have been realised. This has been made possible by better insulated and more airtight building envelopes, balanced ventilation systems with heat recovery and utilization of passive solar heating. On the contrary, due to the increased levels of insulation, air tightness, and demands for comfort, the need for energy efficient cooling has arisen. Therefore it is essential to develop heating/cooling concepts that are passive and/or using very little primary energy.

Due to their high energy efficiency, ground source heat pumps (GSHP) have been under extensive research as a heating/cooling source within the concepts for low and net-zero energy residential houses (Hamada et al. 2000, Sakellari et al. 2004, IEA HPP-AN32-1 2011, Stene 2008, Liu 2008). An increase of the performance factor of these systems, compared to other types of heat pumps, is obtained by using the ground as a heat source with more moderate and balanced temperatures compared to ambient.

Heat to/from a conventional GSHP is extracted/rejected from/to the ground via a ground heat exchanger (GHE). The design of the GHE will affect heat pump system performance, auxiliary pumping energy requirements, and installation costs.

Ground-source heat pump systems for residential houses are often designed to cover around 80% of the total annual heating and cooling demand. Due to that reason these systems are frequently unable to provide the necessary heating or cooling power at peak demand and there is a time mismatch between energy supply and demand. A suitable thermal storage is therefore needed to overcome this time lag.

Thermally activated building systems (TABS) use the large thermal capacities of the building structure as thermal energy storage and are thereby integrated in the overall energy strategy of the building (Meierhans 1993, Olesen 2000, Olesen et al. 2006). Heating/cooling gains during the day are stored in solid floors and slabs, which are then recooled/reheated at an appropriate time by means of a water pipe system – the extracted energy being rejected to the ground using the GSHP system. Through the intermediate storage of energy in the building mass, peaks in energy demand are flattened. In addition, there is no need to instantly supply the heating and cooling demand of the space to the slabs. Heat and cold can be transferred with time shift and at power levels which may differ from the actual demand.

While, in buildings with heavy construction, the concrete slabs provide the necessary thermal mass for the TABS system, there should be found alternative solutions for lightweight buildings. Latent storage in phase-change materials (PCMs) has turned out as being the main focus in ongoing engineering research. PCM-panels with hydronic pipes could be the alternative TABS system for lightweight buildings, where the PCM gives the necessary thermal mass, while the hydronic pipes provide active charging and discharging of the PCM (Koschenz & Lehmann 2004, Kalz et al. 2007).

The aim of the present work is to evaluate and optimize the performance, in relation to thermal comfort and energy consumption, of a GSHP system coupled to thermally activated ceiling panels with incorporated PCM. The concept, being part of the energy supply system of a 75 m^2 low-energy lightweight residential house, will be analyzed through computer simulations using TRNSYS 17 (Klein et al. 2009), for two different climatic locations in Europe, Copenhagen (DK) and Madrid (ES).

2. Case study description

A reference model was developed in order to study the proposed concept of GSHP system combined with TABS-PCM system. The analyses concentrate on the energy performance and thermal comfort achieved by using different ceiling embedded pipes system configurations.

Building envelope

A 75 m^2 one storey single-family lightweight (wooden panels and insulation) residential house has been chosen for this study. The building envelope is well insulated and windows are of triple glazed low energy type. The house is built as a single space except for the bathroom. The total conditioned volume is 220 m^3. In Figure 1 is shown a 3D model and a floor-plan layout of the house. General building information is summarized in Table 1.

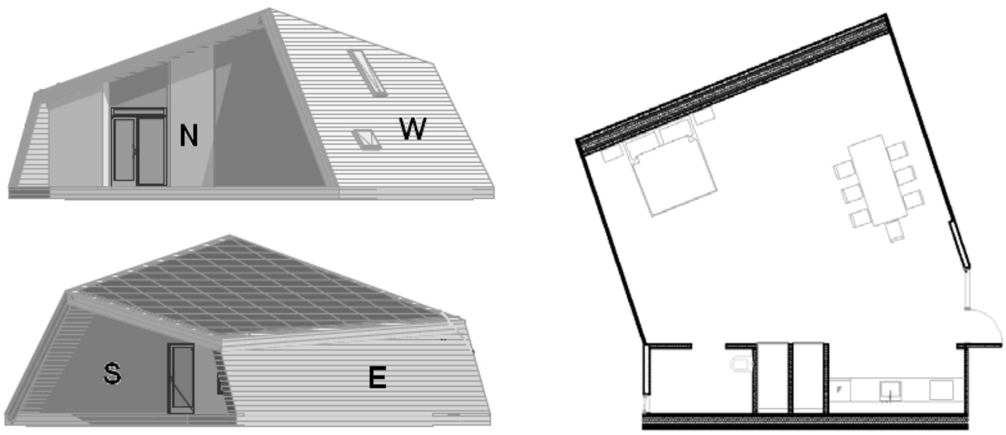

Figure 1. House 3D model and floor-plan layout

The house has a mechanical ventilation system with heat recovery supplying 172 m^3/h. The ventilation system is not intended to be used for heating and cooling purposes but rather to remove sensory pollution and provide the required level of relative humidity in order to achieve a pleasant indoor climate. The supply air temperature is controlled to a minimum of 17°C during the heating season and a maximum of 22°C during the cooling season.

In order to reduce peak cooling loads during summertime, the windows are provided with external shading that is controlled by the zone temperature. When the zone operative temperature exceeds 24°C, external shading (0.7 shading coefficient) is applied on the windows.

Floor heating and ceiling cooling system

The heating need of the house is addressed by embedded pipes in the floor and the cooling needs are addressed by embedded pipes in the ceiling and by the pipes in the floor, if necessary.

The floor system is a sandwich structure of chipboard, heat conductive plate, PEX piping of 13 mm internal diameter at a spacing of 20 cm, and parquet layer (Figure 2). The embedded system is divided in 5 parallel circuits. The system is designed to supply a total water mass flowrate of 250 kg/h. The heating capacity of the floor system is 32 W/m2 (operational floor area is 75 m2).

Table 1. General information for the building.

External Walls	South	North	East	West	Floor	Roof
Area, m^2	19	36	18.1	43.7	75	61
U-value, W/m^2K	0.09	0.09	0.09	0.09	0.09	0.09
Windows	South	North	East	West	Floor	Roof
Area, m^2	14.15	25.6	-	2.24	-	-
U-value, W/m^2K	0.7	0.7	-	0.7	-	-
Solar transmission	0.4	0.4	-	0.4	-	-
Time of the day	6-8; 21-22	17; 19-20	9-16	18	23-1; 3-5	2
Internal loads, W/m^2	6.28	6.51	0.23	8.9	3-32	4.54

The ceiling system is a sandwich structure of polyester board, heat conductive plate, PEX piping of 8.6 mm internal diameter at a spacing of 12.5 cm, and plywood layer for internal finishing. The embedded system is divided in 5 parallel circuits. The system is designed to supply a total water mass flowrate of 250 kg/h. The cooling capacity for the system is 35 W/m^2 (operational ceiling area is 61 m^2).

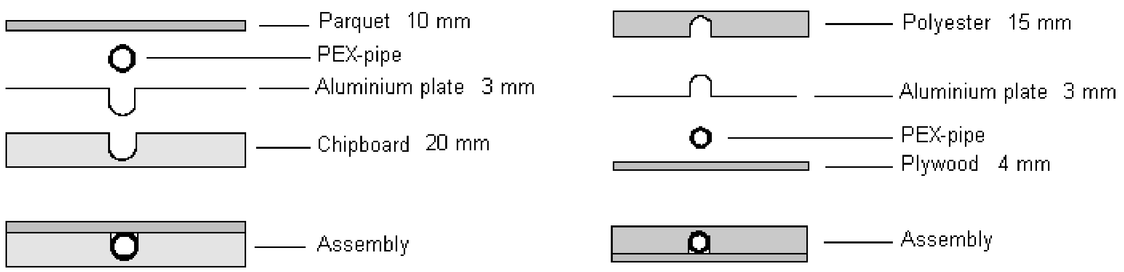

Figure 2. Embedded pipe system: floor structure (left) and ceiling structure (right)

The control of the floor/ceiling heating and cooling system is split up in a central control and a room control. The central control (Figure 3) will, according to the outside climate, regulate the supply water temperature to the floor/ceiling system. The room control (on/off) will then control the water flow rate according to the set-point room temperature. For the heating season operative room temperature set point of 21°C ±1K and for the cooling season operative room temperature set point of 25°C ±1K are selected, according to the recommendations for thermal environment Class II of EN 15251(2007).

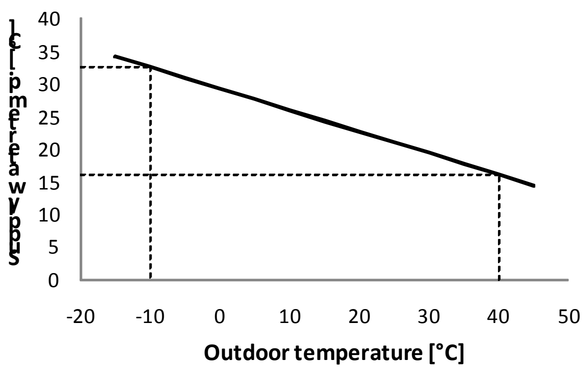

Figure 3. Heating/cooling curve for supply water temperature

PCM ceiling panels with embedded pipes

An important alternative to the ceiling cooling system with embedded pipes is the utilization of thermally activated ceiling panels (TABS) with Phase Change Material (Figure 4). PCM panels with embedded pipes can significantly increase the thermal inertia of the lightweight residential house. The high storage density of the PCM material, and the active utilization of the stored thermal energy by charging/discharging the panel by water driven TABS, will result in shifting the cooling demand from peak hours to off-peak hours, and will provide an efficient means of keeping the operative indoor temperature in the desired comfortable range.

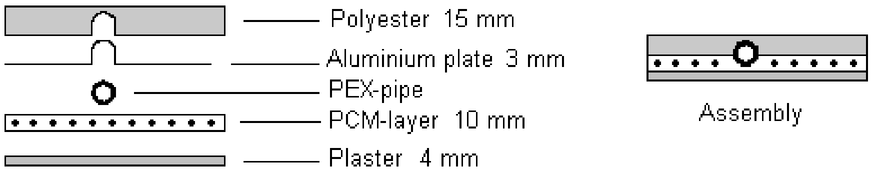

Figure 4. Ceiling panel with PCM

The PCM panels are built as a sandwich structure similar to the ceiling system - polyester board, heat conductive plate, PEX piping of 8.6 mm internal diameter at a spacing of 12.5 cm. The finishing layer of plywood is substituted with a layer of plaster in order to decrease the thermal resistance and increase the heat flux between the PCM and the room air. The hydronic system is designed to supply a total water mass flowrate of 340 kg/h when there is a need for discharging (solidifying the melted material) the PCM.

The PCM materials investigated in the computer simulation study are two salt hydrate materials with melting temperatures of 22°C and 24°C. The latent heat of the salt hydrate materials are the same, however they differ in the melting range and in the crystallization temperature. The specific data of the investigated PCM materials is summarized in Table 2.

Table 2. Thermal properties of the PCM materials

Material	Salt hydrate, SH24	Salt hydrate, SH22
Melting range, °C	22-26	20-24
Crystallization temp., °C	22	20
Spec. latent heat, kJ/kg	145	145

The control of the PCM ceiling system is activated during the cooling season and is similar to the embedded floor/ceiling system, split up in a central control and a room control. The central control (Figure 3) will, according to the outside climate, regulate the supply water temperature to the PCM panels system. The room control (on/off) will then control the water flow rate according to the set-point room temperature for cooling.

The control of the system gives priority to passive utilization of the PCM panels. Heat is absorbed during the day and discharged by the cool night temperatures. The active mode of operation begins when the daily room temperature (6-22 o'clock) exceeds 25°C. The control is set to 'on' during night time (23-5 o'clock), water is run through the embedded pipes, and the PCM material is allowed to discharge the heat absorbed during the day. When the absorbed heat is discharged the control is set to 'off'. During the day, the PCM panels work passively, absorbing heat from the house. In situations when the PCM panels have inadequate capacity to provide the required room temperatures (room operative temperatures exceed 26°C), the floor system is used to provide supplementary cooling during daytime.

The performance of the PCM panels is evaluated using a simulation tool integrated into the numerical simulation environment TRNSYS 17. The tool, developed by Dentel et al. (2010), allows simulating the room behaviour in buildings with PCM in active wall constructions (for e.g. chilled ceilings).

Ground Source Heat Pump System

Heat is extracted/rejected from/to the ground via a GSHP-borehole heat exchanger system. For a small residential house, of the size considered in the present work, it is normally enough to have one borehole. The depth of the borehole depends on the heating/cooling load, the ground thermal conductivity, the natural temperature in the ground, the ground water level, etc. The GHE used was constructed of a single U-pipe inserted in a borehole of a depth of 100 m. The main parameters of the GHE design are listed in Table 3.

Table 3. Ground heat exchanger parameters and soil properties

Pipe inside (outside) diameter, m	0.013 (0.016)
Pipe thermal conductivity, kJ/h.m.K	1.44
Fluid thermal conductivity, kJ/h.m.K	2.066
Fluid specific heat, kJ/kg.K	4.19
Fluid density, kg/m3	1000
Soil density, kg/m3	2400
Soil conductivity, kJ/h.m.K	6.3
Soil specific heat, kJ/kg.K	0.84

The heat pump is a water-to-water type with a nominal output capacity of 2 kW. Catalogue performance data in Figure 5 illustrate the range in efficiency with respect to inlet load and source water temperatures. The heat pump was controlled with an aquastat in order to deliver the required supply water temperature for the floor heating and cooling system with a deadband of ±1K. For the cooling season a passive cooling mode was given priority, in which the heat pump was bypassed and the supply water temperature was conditioned, through a heat exchanger, by the cool fluid circulating in the GHE. When the capacity of the GHE was not sufficient to provide the required water temperature, the heat pump started operation.

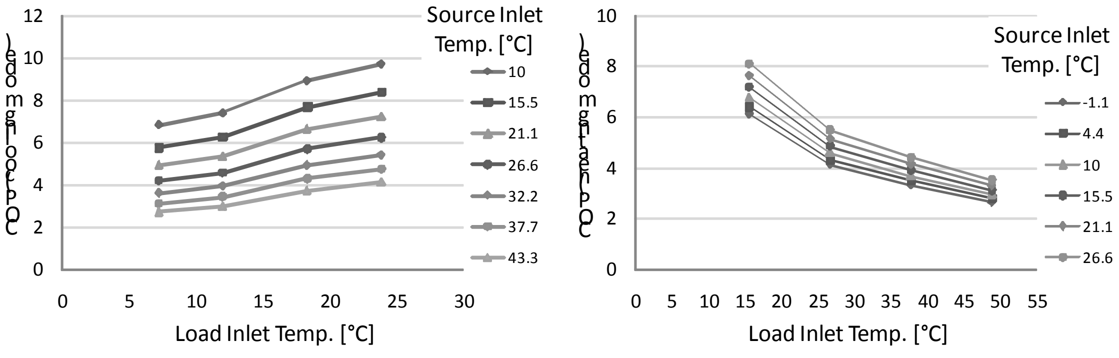

Figure 5. Heat Pump Efficiency – cooling (left) and heating (right) mode

Boundary conditions

The meteorological ambient boundary conditions correspond to the cool climate of Copenhagen (Denmark) and hot climate of Madrid (Spain). The external temperature data for winter and summer design days are -12°C and 30°C for Copenhagen, and -8°C and 40°C for Madrid. Summer period is from 1 May to 30 September, and winter period from 1 October to 30 April.

Floor and ceiling embedded pipe systems for heating and cooling – Case studies

In order to evaluate the performance in relation to energy consumption and indoor climate, three different embedded pipes system designs for heating and cooling the residential house were investigated, Table 4. For heating purposes the system with embedded pipes in the floor is used in all cases. For cooling purposes system with embedded pipes in the ceiling or systems with thermally activated ceiling panels with PCM with melting temperatures of 22°C or 24°C were used. The proposed system designs were replicated for the climatic locations of Copenhagen and Madrid.

Table 4. Heating and cooling systems – Case studies

Case	Location	System for Heating	System for Cooling
CPH 1	Copenhagen	floor embed. pipes	ceiling embed. pipes (+ floor embed. pipes)
CPH 22	Copenhagen	floor embed. Pipes	PCM 22 panel (+ floor embed. pipes)
CPH 24	Copenhagen	floor embed. Pipes	PCM 24 panel (+ floor embed. pipes)
MAD 1	Madrid	floor embed. Pipes	ceiling embed. pipes (+ floor embed. pipes)
MAD 22	Madrid	floor embed. Pipes	PCM 22 panel (+ floor embed. pipes)
MAD 24	Madrid	floor embed. pipes	PCM 24 panel (+ floor embed. pipes)

3. Results and discussion

Energy Consumption

In Figure 6 are presented the results for the annual energy consumption for the three system configurations. It can be seen that for the climatic location of Copenhagen, there is no significant difference between the performance of the three systems. The use of PCM panels gives slight advantage compared to the system with embedded pipes. The passive utilization of the PCM panels during winter time results in 3% (PCM with 24°C melting temperature) to 6% (PCM with 22°C melting temperature) decrease of the annual energy consumption for heating. Due to the low energy demand for cooling, there is no distinguishable advantage of the use of PCM panels compared to the embedded pipes system.

For the climatic location of Madrid, the advantage of adding thermal mass in the house, by using the PCM panels system, could be clearly distinguished. The passive utilization of the PCM panels during winter time results in 9% (PCM with 24°C melting temperature) to 12% (PCM with 22°C melting temperature) decrease of the annual energy consumption for heating. For the cooling season, the systems with PCM panels use about 50% less energy for providing the necessary cooling for the house.

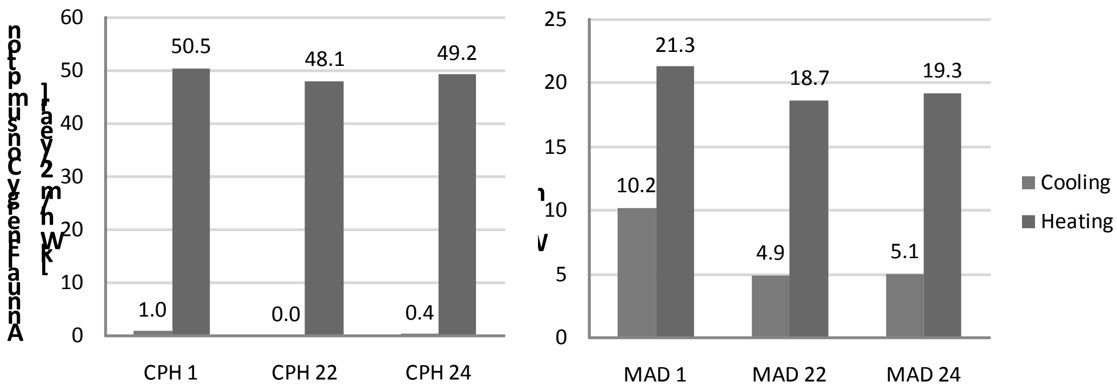

Figure 6. Annual energy consumption

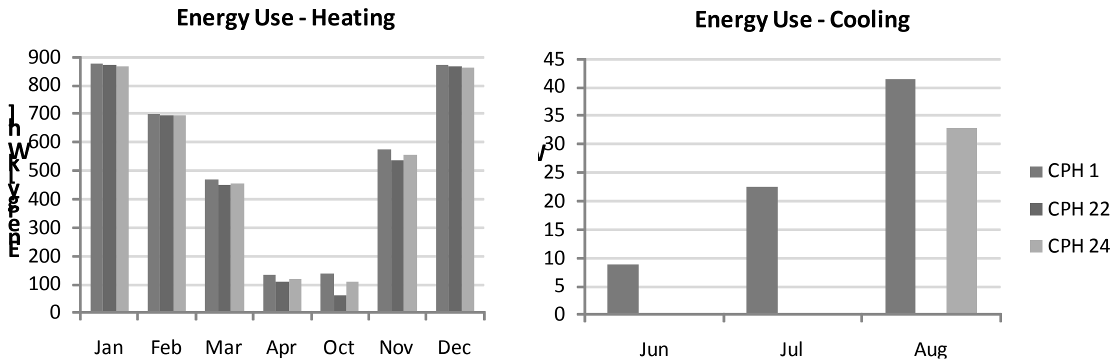

Figure 7. Energy consumption for heating and cooling on monthly bases, for Copenhagen

In order to further understand the benefits of using the different systems, the energy consumption for heating and cooling on monthly bases is shown in Figure 7 (for Copenhagen) and Figure 8 (for Madrid).

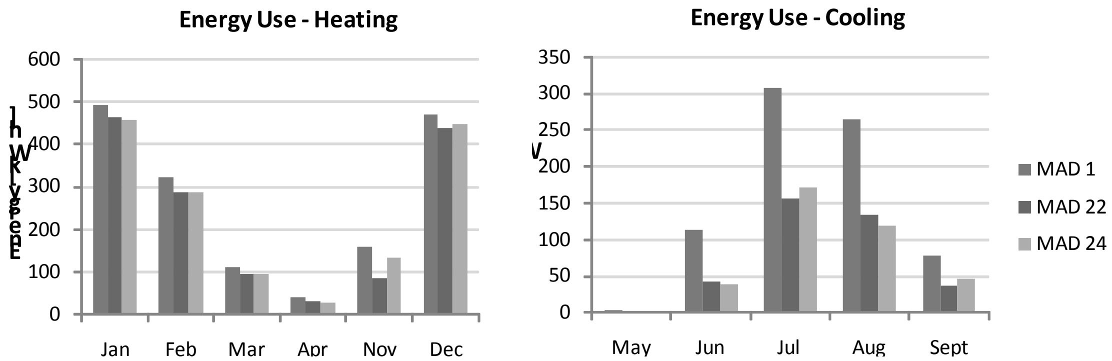

Figure 8. Energy consumption for heating and cooling on monthly bases, for Madrid

For the heating season it can be seen that the systems with PCM panels have advantage during the transition months of April, October and November, when there is a higher room temperature variation during day and night, which enhances the passive utilization of the PCM material. For the cooling season, the added thermal mass by using the PCM panels has almost completely removed the need for active cooling for the location of Copenhagen. For the climatic location of Madrid, significant energy need reductions for cooling are observed during the whole cooling season, when the systems with PCM are used.

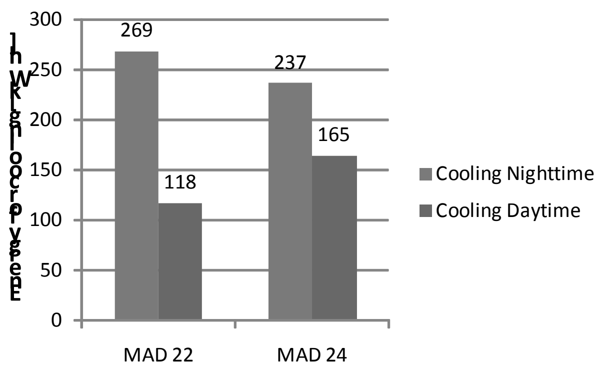

Figure 9. Energy supply for cooling during daytime and nighttime (peak load shifting), for Madrid

In Figure 9 is shown the cooling energy delivered during nighttime (PCM panels) and the supplementary cooling provided instantaneously by the embedded pipes in the floor during daytime, for the two systems with PCM panels for the location of Madrid. The increased thermal inertia of the lightweight residential house, by using the systems with PCM, has resulted in shifting large part of the cooling demand of the house from the peak hours during the day to off peak night hours. Compared to the system with ceiling embedded pipes, there has been no need to instantly supply all the cooling demand of the space. Cooling has been transferred with time shift and at power levels much lower than the actual demand.

GSHP system efficiency

In Figure 10 and Figure 11 are shown the results for the GSHP system efficiency in terms of system coefficient of performance (including ground source heat pump coefficient of performance and energy used by circulation pumps).

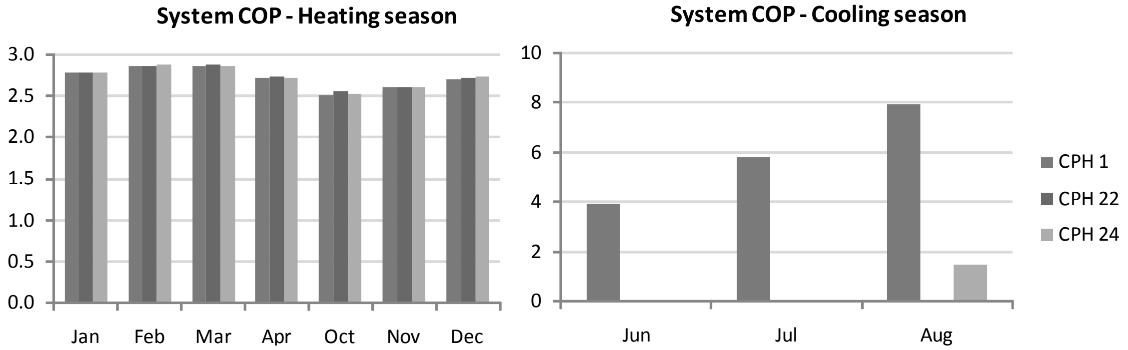

Figure 10. GSHP system efficiency, for Copenhagen

For the heating season, no any advantage or disadvantage by using any of the three system configurations can be seen. For the cooling season, the cooling energy needed is provided by free cooling, where the GSHP has not been used in any of the three studied cases. All the necessary energy for cooling is provided by using only the ground heat exchanger.

It can be seen that during the cooling season the system with embedded pipes has much higher system COP compared to the systems with PCM panels. However, that cannot be an indicator for being the better choice of system, since, as previously shown, the total energy consumed by the system with embedded pipes is twice as much as the systems with PCM panels. The lower system COP of the systems with PCM panels could actually be as a result of the low energy demand for cooling, where there is a high contribution of the electrical energy used by the circulation pumps to the total energy used for cooling.

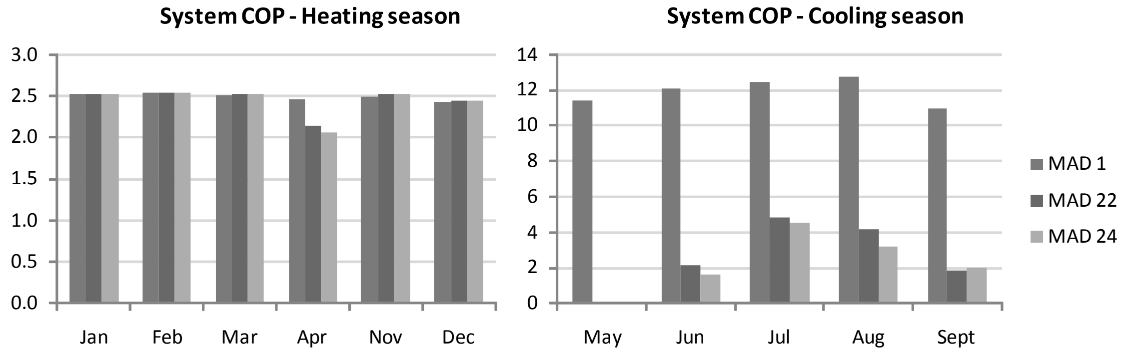

Figure 11. GSHP system efficiency, for Madrid

Indoor thermal environment and passive and active thermal mass utilization

Since one of the main criteria for system performance is related to the provided thermal environment, in Figure 12 and Figure 13 are shown the indoors operative temperature variations during representative weeks from the heating and cooling seasons for the two climatic locations considered. It can be seen that all system configurations considered have proved capable of providing the required thermal environment.

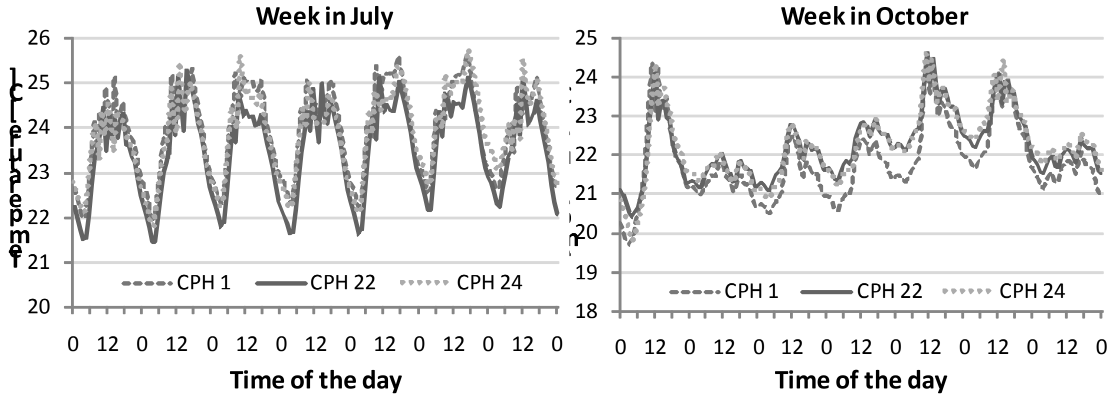

Figure 12. Indoors operative temperature variation, for Copenhagen

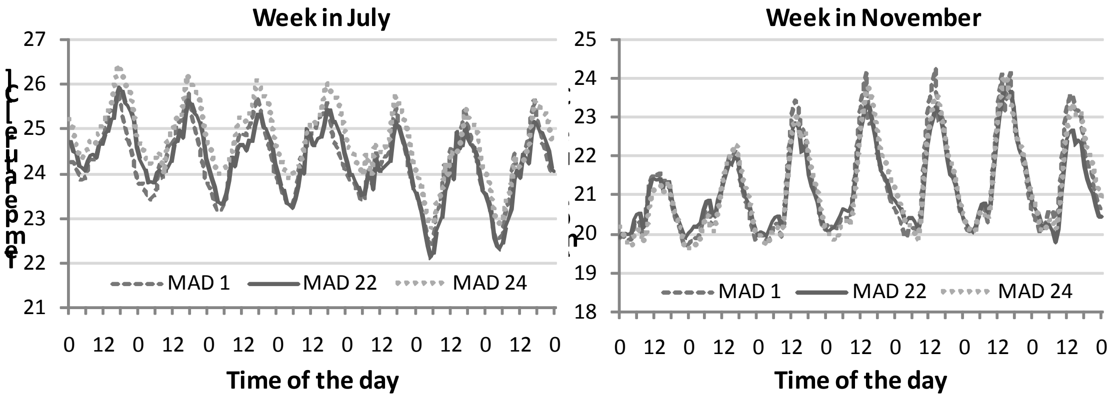

Figure 13. Indoors operative temperature variation, for Madrid

As previously discussed, the increased thermal mass of the house, by the use of PCM panels, has resulted in decrease of the annual energy consumption for heating and cooling. The active utilization of the PCM panels has resulted in significant load shifting from peak day hours to nighttime. However, the main driving force for the energy consumption reduction should be attributed to the passive utilization of the PCM during both the heating and the cooling season.

Table 5. Energy consumption during representative weeks from the heating and cooling seasons

Case	Energy consumption [kWh]			
	Heating – Week in Oct/Nov		Cooling – Week in July	
	Active	Passive	Active	Passive
MAD 1	103.9	0	39.2	0
MAD 22	80.5	23.4	15.8	23.3
MAD 24	96.8	7.1	21.6	17.6
CPH 1	8.6	0	6.6	0
CPH 22	0	8.6	0	6.6
CPH 24	4.3	4.3	0	6.6

In Table 5 is shown the energy demand of the house covered by passive and active means, for the two representative weeks from the heating and cooling seasons. It can be seen that for both periods significant part of the heating and cooling demand is covered by passive utilization of the PCM. That phenomenon can be correlated with the indoor temperatures, shown in Figure 12 and Figure 13, which daily variation is within the melting range of the PCMs used.

4. Conclusions

The combination of GSHP with low temperature heating and high temperature cooling integrated in the building structure is an energy efficient concept to provide thermal comfort in residential buildings. Combining the system with increased thermal mass of the building by using phase change material (PCM) helps decreasing the peak loads, transfer the need for heating and cooling to times of the day with less peaks on the energy grid, and decreasing the annual energy consumption for heating and cooling.

For both geographical locations the energy supplied for cooling has been obtained by passive means, without use of the heat pump, utilizing only the ground heat exchanger.

From the presented results about energy use and thermal environment, the systems with PCM panels have shown clear advantage compared to the system with embedded pipes. It should be pointed out the importance of PCM melting/solidifying temperatures, in order to integrate the TABS-PCM system in the overall energy strategy of the residential unit, and in providing the required thermal comfort in the house. The use of PCM with melting temperature of 22°C has shown a tendency to be the more favorable choice of material. However, there should be done further in-depth analyses and investigation of control strategies to better understand and utilize the full potential of the systems with PCM panels.

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BUILDING THERMAL ENERGY STORAGE – CONCEPTS AND APPLICATIONS

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Abstract

The use of Thermal Energy Storage (TES) in buildings in combination with space heating, domestic hot water and space cooling has recently received much attention. A variety of TES techniques have developed over the past decades, including building thermal mass utilization, Phase Change Materials (PCM), Underground Thermal Energy Storage, and energy storage tanks. In this paper, a review of the different concepts for building or on-site integrated TES is carried out. The aim is to provide the basis for development of new intelligent TES possibilities in buildings.

TES systems for cooling or heating capacity are utilized in applications where there is a time mismatch between the demand and the economically most favourable supply of energy. TES can provide short term storage for peak shaving as well as long term storage for the introduction of renewable and natural energy sources.

Sustainable buildings need to take advantage of renewable and waste energy to approach ultra-low energy buildings. Utilization of low-exergy heating and cooling sources requires that energy storage is integrated into sustainable building design. A coordinated set of actions for improved TES designs are needed if the potential benefits are to be fully realized. Well designed systems can improve building's energy efficiency and comfort level, yielding significant cost savings and promising payback period.

Keywords: thermal energy storage, ground storage, PCM, TABS, energy storage tanks

1 Introduction

Energy demands in commercial, industrial and residential sectors vary on daily, weekly and seasonal basis. These demands can be matched with the help of Thermal Energy Storage (TES) systems that operate synergistically and are carefully matched to each specific application.

The use of TES for heating and cooling applications has recently received much attention (Dincer, 2002 and 2011). A variety of new TES techniques have been developed over the past four decades. Well designed systems can reduce initial and maintenance costs and energy use and demand (Dincer, 1996 and 1997).

Thermal energy storage is the temporary storage of high- or low-temperature energy for later use. Different examples about the efficient utilisation of natural and renewable energy sources, cost savings and increased efficiency achievable through the use of TES could be considered.

In continental climates, it is possible to store heat from the warm summer months for use in winter, while the cold ambient temperatures of winter can charge a cold store to provide cooling in summer. This example of seasonal storage can meet the energy needs caused by seasonal fluctuations in temperature. Such a scheme requires great storage capacity because of the large storage timescales. The same principle can be applied on a small scale to smooth out daily temperature variations. For example, solar energy can be stored during the day and used for night heating. Another example is the use of thermal storage to take advantage of off-peak electricity tariffs. Chiller units can be used to cool a thermal storage at night, when the cost of electricity is relatively low. The storage then provides cooling for air conditioning throughout the day. In that way electricity costs are reduced, the efficiency of the chiller is increased and the peak electricity demand for supply utilities is reduced.

2 Benefits of Thermal Energy Storage

Dincer (2002, 2011) pointed out that the advantages of TES exceed the disadvantages. The benefits of utilising TES systems can be divided in three groups – benefits for the building owner, benefits for the environment and society, and benefits for the energy provider; summarised in Table 1.

Table 1: *Benefits of Thermal Energy Storage*

Groups	*Benefits of TES*
Benefits for the building owner	• Reduced heating/cooling costs, system's components size and initial costs • Improved indoor environmental quality • Less expensive electricity rates due to increased load factor for electricity
Benefits for the environment and society	• More viable utilisation of renewable energy resources (i.e., solar) • Energy distribution with low line losses and high generation efficiencies • Eliminating the need for additional power plants • Reduced source-energy consumption => fewer polluting emissions
Benefits for the energy provider	• Reduced peak electrical demand; increased efficiency of energy production • Increased utility's load factor

3 Criteria for design and evaluation of TES systems

The different TES concepts have different characteristics, possible applications, strengths and weaknesses. There are numerous criteria to evaluate TES systems and applications such as technical, environmental, economic, energetic, sizing, integration, and storage duration, Dincer (2011).

The first step of a TES project is to determine the energy load profile of the building. Parameters influencing the demand and load profile of the building are use of the building, internal loads, and the climatic conditions. Following steps are to determine the type and amount of storage appropriate for the particular application, the effect of storage on system performance, reliability and costs, and the storage systems or designs available.

It is useful to characterise the different types of TES depending on the storage duration. Short-term storage is used to address peak loads lasting from few hours to a day in order to reduce the sizing of the system and take advantage of energy-tariff daily structures. Long-term storage is used when waste heat or seasonal energy loads can be transferred with a delay of a few weeks to several months.

Related to the amount of storage required, a need exists for improved TES-sizing techniques. Realised projects reveal both undersized and oversized systems. Undersizing can result in poor levels of indoor comfort, while oversizing results in higher initial costs and waste of electricity or other primary energy sources if more energy is stored than is required.

The effect of TES on the overall energy system performance should be evaluated in details. The potential for more effective use of thermal energy equipment and the storage integration with the building energy supply system has to be investigated.

The economic justification for storage systems requires that the annualized capital and operating costs for TES be less than those required for primary generating equipment supplying the same service loads and periods.

4 Building TES systems and applications

A variety of TES techniques for space heating/cooling and domestic hot water have developed over the past decades, including Underground TES, building thermal mass, Phase Change Materials, and energy storage tanks. In this section, a review of the different concepts is presented.

4.1 Underground TES concepts

Seasonal thermal energy storage requires large inexpensive storage volumes and the most promising technologies were found underground. Underground Thermal Energy Storage (UTES) has been used to store large quantities of thermal energy to supply space cooling/heating, and ventilation air preheating. Energy sources include winter ambient air, heat-pump reject water, solar energy, process heat, etc. The most common UTES technologies are aquifer storage (ATES) and borehole storage (BTES) (Nordell, 2000). It is not possible, for geological or geo-hydrological reasons, to construct these systems at any location. Borehole systems are the most generally applicable ones.

The use of seasonal thermal energy storage can substantially reduce the cost of providing solar energy systems that can supply 100% of buildings energy needs. Utilising the ground as a seasonal storage of solar energy has been used in a number of countries in conjunction with district heating systems, Figure 1.

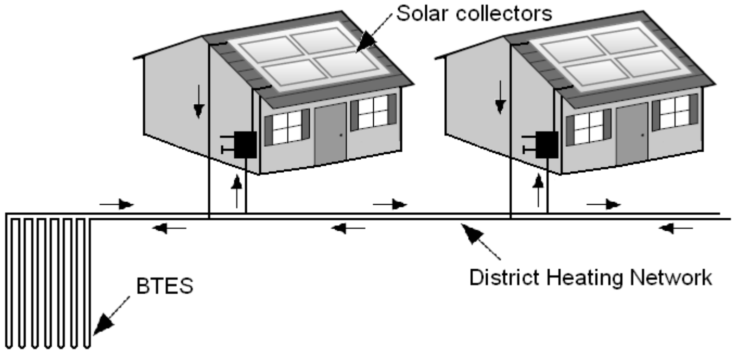

Figure 1. Seasonal storage of solar energy

The solar system in Anneberg (Nordell et al, 2000 and Lundh et al, 2008), is a good example of how solar heat is stored during summer and used for heating of family houses during winter, through low temperature floor heating systems.

In a demonstration plant in Neckarsulm (Schmidt et al, 2005), a residential and commercial area is connected to a central solar heating plant with seasonal storage. During the last years of operation solar fraction of 39% has been monitored. According to simulations the ground heat store will have an efficiency of about 65%, when a quasi-steady-state of operation of the storage media is reached.

In seasonal BTES of solar energy, high temperatures usually result in the storage at the end of the summer period. Such high temperatures have two drawbacks. First, the return temperature to the solar collectors is high which leads to low solar collector efficiencies. Second, heat losses from the storage are high: ~ 60% of the injected heat (Sibbit et al., 2007). In Chapius et al. (2009) is proposed a new strategy to overcome these drawbacks, by keeping the storage at a lower temperature.

Although different studies have shown potential for “free” high/low temperature BTES systems for space heating/cooling, the focus of innovative systems lies in the concept of Ground Source Heat Pumps with BHEs for combined heating and cooling applications, Figure 2. In this case heat pump is employed to decrease or increase the storage temperature for cooling or heating (Nordell et al., 1998).

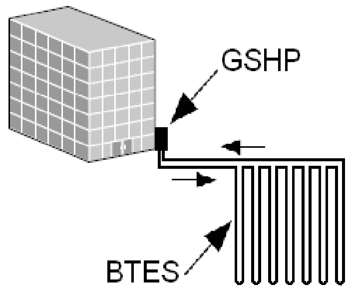

Figure 2. GSHP with BHEs

Ground source heat pump systems (GSHP) have found broad application worldwide (Rybach et al., 2000 and Lund et al. 2004). The GSHP technology can offer higher energy efficiency for air-conditioning compared to conventional systems.

Desmedt et al. (2008) provided an overview of the results from a feasibility study to implementation phase of vertical BHEs in combination with GSHPs for a Belgian office building. The results show that primary energy savings can be obtained compared to conventional technologies. The ground storage system supplementary investment is paid back in 8 years.

A large scale BTES system for heating and cooling of Ontario Institute of Technology is presented in Dincer (2011). Monitoring results show annual energy savings for heating and cooling of 40% and 16% respectively. A payback period of 7.5 years is expected.

For UTES systems one of the most important factors is the required temperature level for the heating/cooling case involved. UTES systems are more efficient if the temperature requirement for space heating is low and for cooling is high. Using low-temperature heating/ high-temperature cooling systems will result in high COP for the whole system. Thermo-active building systems (TABS) for commercial buildings and floor heating systems for residential buildings have proven successful in practice.

In Fellin et al. (2003) simulation analysis of an office building, equipped with TABS is presented. Two different climatic zones and two possibilities of plant (traditional and an innovative, based on a GSHP) have been studied. The results show that TABS could ensure good comfort conditions in office buildings with heating loads in the range of 10 – 30 W/m² and moderate cooling loads, in the range of 30 – 60 W/m². By using a ground coupled heat pump, more than 40% of energy may be saved compared to the use of conventional system.

4.2 Building Thermal Mass Activation

Thermal mass is defined as the mass of the building that can be used to store thermal energy for heating/cooling purposes. In general the application has been found to be particularly suitable for climates with big diurnal temperature variations. The brief overview of concepts for activation of thermal mass for enhancing the energy efficiency of buildings presented here is focusing on Passive Thermal Mass Systems and Thermo-Active Building Systems (TABS).

In a simulation study evaluating the cooling energy of high rise residential buildings in Hong Kong (Bojic et al., 2005), results indicate that if the walls' thermal capacity is reduced, it would lead to a 60% increase of the cooling energy demand.

Givoni (1998) investigation shows the effectiveness of passive thermal mass and night ventilation in lowering the indoor air temperature during daytime for building with high thermal mass.

Cooling by night-time ventilation can be used if night temperatures are low enough to release heat from the building's thermal mass. For Europe the climatic potential for passive cooling of buildings by night-time ventilation has been analyzed in Artmann et al. (2007). It was shown that in Northern Europe there is significant potential for cooling by night-time ventilation. In Central, Eastern and Southern Europe passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. In such cases, Thermo-active building systems are considerably more effective.

TABS systems are used in multi-storey office buildings with a low heating load in winter (10-30 W/m^2) and a moderate cooling load in summer (30-60 W/m^2). With TABS the large thermal capacity of the building structure is used as energy storage and is thereby integrated in the overall energy strategy of the building. By utilising TABS, peaks in energy demand are flattened, and heat and cold can be transferred with time shift and at power levels which may differ from the actual demand.

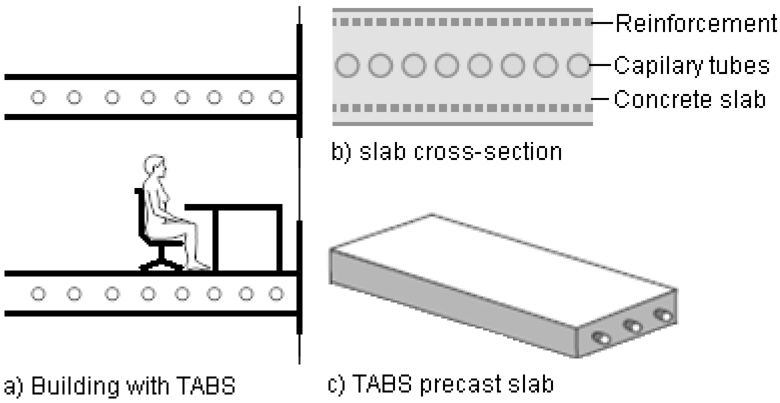

Figure 3. Thermo-active building systems (TABS)

Moreover, the large areas of the thermo-active surfaces allow for substantial heat flows between room and structure, even at relatively low temperature differences. For these reasons TABS are suitable for the application of low temperature heating and high temperature cooling sources, such as geothermal energy, groundwater or outside air (Koschenz et al., 1999 and Lehmann et al., 2007).

A comprehensive analysis of primary energy consumption of TABS is given by Henze et al. (2008), by a simulation study comparing the primary energy and comfort performance of ventilation assisted TABS system relative to a conventional VAV system. TABS heating is accomplished using a geothermal heat pump and TABS cooling using a geothermal heat exchanger. A primary energy savings of 20% were observed for the case with TABS.

A study by Rijksen et al. (2010) presents general guidelines for the required cooling capacity of an entire office building using TABS. Reductions up to 50% of the cooling capacity for a chiller can be achieved using TABS.

Results of Lehman et al. (2011) study, in Central European office building, show that the energy efficiency of TABS is significantly influenced by the hydronic circuit topology used. With separate zone return pipes energy savings of approximately 20–30% of heating as well as cooling demand, can be achieved, compared to common zone return pipes.

4.3 Phase Change Materials

The investigation of Phase Change Materials (PCM) for heating and cooling applications in buildings has a long history. Mehling et al. (2008) presents different concepts and potential applications of PCM for heating and cooling in buildings.

The applications of PCM can be divided into temperature control and storage of heat or cold with high storage density. The potential for temperature control are related to the potential for increasing the building heat storage capacity or thermal mass. In such applications, the focus is on the temperature regulation and the PCMs used should have phase change temperatures within the comfortable temperature range. In applications for the storage of heat or cold with high storage density, the focus is on the amount of heat supplied. In heating/cooling systems storage can be used to optimise the performance of the system in case of fluctuating demand or supply for heat or cold. The main advantage is the high storage density in small temperature intervals. In these applications, the PCM phase change temperature is significantly different from the comfortable temperature range.

The potential of using PCM in building materials to reduce temperature fluctuations is quite large, especially in lightweight buildings. Microencapsulated PCM incorporated into gypsum plasterboards or plasters has been developed commercially by different companies (e.g., microencapsulated paraffin with melting temperature in the range 23-26°C).

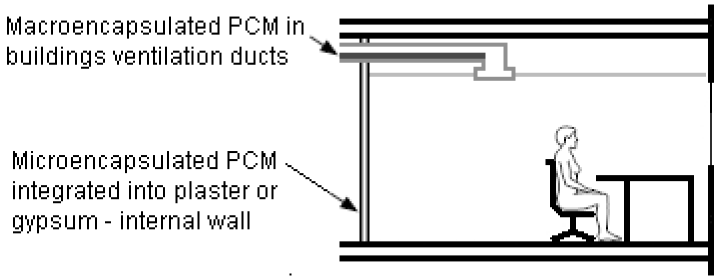

Figure 5. Examples of PCMs integrated in buildings

Another option is to integrate microencapsulated PCM into concrete. In an experimental study (Cabeza et al., 2007), of two concrete buildings, one of which includes 5% microencapsulated PCM in some walls, a temperature reduction of up to 4°C was achieved with the use of PCM. The results show the importance of night cooling to achieve this full-cycle every day.

It is important to check if the heat is not only stored, but also if it can be discharged on a daily cycle. In Neeper (2000) is presented a study on the thermal dynamics of a PCM wallboard under daily temperature variations. The results show that the daily storage capacity is limited to 300-400 kJ/m^2.

PCM can be integrated also in building systems. This approach can benefit from the fact that the PCM can be integrated in a way that the active ventilation leads to a better heat transfer coefficient at the surface of the PCM.

All examples till now have used air as heat transfer fluid and cold night air as a cold source. Using a liquid as a heat transfer fluid for heat rejection allows the use of more reliable natural cold sources like ground water, or artificial cold sources like compression or absorption chillers. On the demand side, water based storage systems for room air conditioning like TABS are already known. For these types of systems, use of PCM is also possible.

Cold storage is very common in conventional air-conditioning and industrial refrigeration systems. Because of its availability, high storage density, and low cost, water-ice is still by far the most widely used PCM. However, systems using other PCM than water-ice, with melting temperatures up to 20°C (8.3°C are most common ones) have also found broad application.

Seasonal cold storage by PCM (snow or ice storage) comprises two sources: natural ice and snow from precipitation, or snow or ice produced artificially using natural cold like cold air. In both cases the energy for cooling is practically free. Examples of both concepts are the Sundsvall Hospital Snow Cooling Plant in Sweden, and the Canadian Ice box/Fabrikaglace concept (Nordell et al., 2007).

The experience from the last decade shows that PCM applications for space cooling have found wider application however there are potential applications for space heating as well.

Solar air heating can be combined with the supply of fresh air in an energy efficient manner. A problem using air as heat transfer medium is that air stores too little heat due to its low heat capacity. The use of PCM seems promising because of the high heat storage density and because the PCM can have a regulating effect on the supply air temperature.

4.4 Energy Storage Tanks

TES tanks for use in heating, cooling, and domestic hot water applications have received increasing attention in recent years. The TES tank system most commonly employed at present is sensible, utilizing water as the storage medium. An effective system of that type should be stratified; it should hold separate volumes of water at different temperatures, with minimum mixing between them even during charging and discharging periods. TES tanks using latent storage have also found application. Typical systems employ the use of water-ice, ice-slurry, PCM, and PCM-slurries.

Large TES tanks for seasonal storage, as well as small tanks for diurnal or buffer storage are used in practice. The storage can be designed for peak shaving, for part- or full-load capacity.

TES tanks for seasonal storage can be designed to retain heat deposited during summer months for use during winter. The heat is typically captured using solar collectors. The tanks are sized to meet part or all of the heating and hot water requirements whether it is residential or commercial building.

Improving the thermal stratification of the stored water in solar energy systems is important since it can significantly improve the collector and system efficiency. Lavan et al., (1977) shows that even at very large flow rates, thermal stratification in hot water storage system can be maintained in cylindrical tanks.

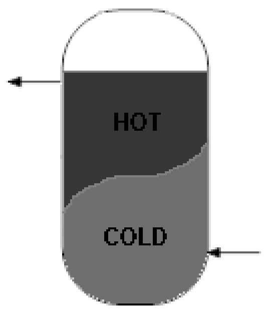

Figure 5. Thermally stratified hot-water storage tank

In Novo et al. (2010) a review on seasonal heat storage tanks and comparison with other ground storage possibilities is presented, focusing on their application in central solar heating systems.

A multi-tank liquid-water system for storing low-temperature solar-derived heat is investigated experimentally and analytically by Mather et al. (2002). The main advantages over single tank systems are foreseen to be a reduced installation cost plus reduced engineering costs.

Except for heat storage, TES tanks for cold storage are very common in conventional air-conditioning applications. Different storage includes water, water-ice, ice-slurry, PCM, PCM-slurries.

Analyses of the stratification decay in vertical cylindrical cool storage systems presented by Nelson et al. (1999) show that the degree of thermal stratification depends upon the length to diameter ratio, wall thickness to length ratio, the thermo-physical properties of the material of the storage tank, the type and thickness of the insulation, and the design of the water admission system.

5 Sustainable Buildings and Thermal Energy Storage

Thermal energy storage is advanced energy technology and there has been increasing interest in using it for thermal applications such as domestic hot water and space heating/cooling. TES has often been applied in standard buildings with the objective to demonstrate that the energy storage techniques could be successfully applied rather than to optimize the building performance. Indeed the design of the building and the design of the energy storage were often not coordinated and energy storage simply supplied the building demand whatever it might be.

Sustainable buildings need to take advantage of renewable and waste energy to approach ultra-low energy and zero emission buildings. Such buildings will need to apply thermal energy storage techniques customized for smaller loads and community based thermal sources. Lower exergy heating and cooling sources will be more common. Utilization of low-exergy heating and cooling sources requires that energy storage is intimately integrated into sustainable building design.

A coordinated set of actions for improved TES design and sizing is needed if the potential benefits are to be fully realized. Well designed TES systems can reduce initial and maintenance costs and can significantly reduce energy use and demand. Increased flexibility of operation, improved indoor environmental quality, conservation of fossil fuels and reduced pollutant emissions are other benefits.

At present IEA ECES Annex 23 “Applying Energy Storage in Buildings of the Future” is dealing with applying of energy storage in ultra-low energy buildings.

6 Conclusions

The present literature review study identifies the characteristics, possible applications, strengths and weaknesses of the different TES concepts. It aims at investigating and providing the basis for the development of new intelligent TES possibilities in buildings.

The study presents the use of TES in buildings for space heating/cooling and domestic hot water. TES concepts, including Underground Thermal Energy Storage, Building Thermal Mass, Phase Change Materials, and Energy Storage Tanks are described. The different energy storage concepts have very different characteristics, possible applications, strengths and weaknesses. Insight is given in the utilisation of solar energy and cold TES.

The selection of TES system mainly depends on the storage period required, economic viability, operating conditions, and so on. Specific parameters that influence the viability of a TES include facility thermal loads, thermal load profiles, availability of waste or excess thermal energy, electrical costs and rate structures, type of thermal generating equipment, and building type and occupancy. The economic justification for TES systems usually requires that annual capital and operating costs are less than the cost for conventional systems and equipment supplying the same service loads and periods. Well designed systems can reduce initial and maintenance costs and energy use and demand, and improve indoor environmental quality. A coordinated set of actions for improved TES design is needed if the potential benefits are to be fully realized.

Although the different energy storage solutions have found many applications in practice, it is still not clear how these can best be integrated into ultra-low energy and zero-emission buildings, capable of being replicated in a variety of climates and technical capabilities. Detailed studies on the dynamic performance and control strategies of the energy storage systems for different building types, weather conditions and user behaviour should be performed. Advanced design strategies for building and on-site integrated thermal energy storage solutions should be developed.

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